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SEDIMENT VARIATION IN A BRAIDED REACH OF THE SUNWAPTA RIVER, ALBERTA

by

©

MARTIN DAWSON

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
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OF MASTER OF SCIENCE

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EDMONTON, ALBERTA
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FACULTY OF GRADUATE STUDIES AND RESEARCH

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John Shaw

Supervisor

R B Rains

Date 20 September, 1982

ABSTRACT

Statistical analyses of downstream grain size variations in an 11km braided reach of the Sunwapta River shows that there are significant deviations from the theoretical model of an exponential decline in grain size downstream (Sternberg 1875). Two sources of variation from the expected relationship may be determined: variability between sub-reaches and variability within sampling transects. The former source of variability can be attributed not only to the effect of tributary inputs but also to differential rates of aggradation and degradation within and between the sub-reaches. Where there is a tributary input of coarse sediment three principal effects may be noted;

1) Bedslope decreases upstream and increases downstream of the tributary.

2) Grain size increases downstream of the tributary.

3) Diminution rates increase both upstream and downstream of the tributary.

The cause of the variation within sampling transects cannot be identified by statistical methods, but, examination of grain size differences over small braid bars indicates that this is the result of essentially random, site-scale factors. The variability demonstrated for the downstream changes in grain size suggests that caution should be used in applying proximal to distal interpretations of fluvial gravel deposits. Diminution coefficients for distinctive lithologies in the reach are anomalous in that the quartzites demonstrate greater values than the limestones. This anomaly is tentatively ascribed to a greater rate of breakage for quartzite clasts and the lag deposition of a coarse quartzite input at the head of the reach. In conjunction with morphological evidence the diminution coefficients show that, in the proximal areas of the reach, limited degradation is occurring. In more distal areas higher values for the diminution coefficients indicate that there is limited aggradation. Sediment sorting improves downstream with two trends being identifable upstream and downstream of the major tributary, Diadem Creek.

Clast roundness increases rapidly in the initial 1km away from the head of the reach and away from Diadem Creek. Upstream of Diadem Creek the variation in the data is probably best approximated by two separate functions describing the initial, rapid, increase in roundness and the downstream, less rapid, change in roundness. Evidence of

trends in other measures of clast morphology is unconvincing, except downstream of Diadem Creek. This is at variance with some other field studies (Bradley *et al* 1972) which have shown distinctive relationships.

Mapping of grain size variation on selected braid bars in the gravel permitted the development of a model of braid bar development with three essential elements;

1) The formation of a nucleus by in-channel deposition or the delimitation of the bar outline by channel migration and avulsion.

2) The secondary modification of the original area by lateral accretion and overbank flow.

3) The limited, tertiary modification of the surface by small overbank flows at later high flow stages.

It is suggested that many of the sorting trends on braid bars are the result of the reorganisation of previously emplaced sediments by overbank flow and that, in general, braid bars show a sediment fining downstream and away from active channels.

ACKNOWLEDGEMENTS

This study would not have been possible without the assistance of many persons and organisations. Parks Canada is sincerely thanked for their issuance of a research and collecting permit, without which the fieldwork could not have been conducted. Accommodation at the field location was provided by the Canadian Youth Hostels Association. Invaluable logistic assistance, advice, and companionship in the field were given by fellow graduate students Peter Ashmore and Carolyn King.

Considerable benefit was derived from discussions with a number of people, in particular Dr Francis Hein and Peter Ashmore, who listened to many of my formative ideas and offered advice and sources of information. The final text of the thesis contains a number of revisions at the suggestion of Dr Emlyn Koster and Dr Bruce Rains. Dr Rains is sincerely thanked for his accurate proof-reading of the final draft. The production of the maps of the braid bars would not have been possible without the advice and assistance of Jeff Lester and other members of the cartographic staff in the Department of Geography. Jack Chesterman and Randy Pakan, with great patience, expertly reproduced the maps contained in this thesis. Finally, I must thank my supervisor, Dr John Shaw, for his continued patience, interest and advice throughout my graduate studies at the University of Alberta.

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1. INTRODUCTION

Braided rivers form distinct fluvial sedimentary environments characterised by anabranching systems of channels, divided by large accretional areas and smaller scale depositional units, the latter features being submerged at high stages. Braided channel patterns are not stable, particularly under high flow conditions. The process of pattern change is a complex function of the accretion of unit bars in the channels, the lateral erosion of banks and the formation of new channels by avulsion, often along the courses of former channels (Hein 1974, Ashmore 1979 and personal communications). Such channel changes result in considerable reworking of accretional areas. This usually involves extensive differential transport of sediment.

Previous sedimentological studies of braided systems have largely focused on sedimentation processes and the development of depositional models (Williams and Rust 1969, Rust 1972, Miall 1977, Hein and Walker 1977, and others). Through such studies it is recognised that sedimentary patterns vary within, and between, studied locations. This realisation led to the development of, for instance, models of proximal and distal sedimentary sequences (Miall 1977). However, there have been few studies, with respect to braided environments, of the variations in sediments as a function of distance and of the influence of multiple sources on sedimentary patterns (Church 1972, Bradley, Fahnestock and Rowenkamp 1972, Ballantyne 1978). It has also been shown that the hydraulic geometry and channel patterns of braided reaches vary with distance downstream (Fahnestock 1963, Nordseth 1973, Rice 1979).

The principal aims of this thesis are to;

1) examine downstream variations in sediment size and sorting,

2) identify possible causes of variation about the observed downstream relationships, for instance, tributary sediment inputs,

3) examine downstream variations in particle roundness and form,

4) examine variations in sediment size over local depositional areas, such as braid bars, and to consider the mechanisms by which patterns of sediment size develop.

1.1 The Field Area

The location of this study is a reach of the Sunwapta River, Jasper National Park, Alberta, Canada (Fig 1.1). The river is discontinuously braided in the upper 25 km of its 50 km length, with the most extensively braided section occurring approximately 12 km from the source. This reach is well defined and is bounded on the upstream end by the Sunwapta Gorge and at the downstream end by a large alluvial fan (Fig 1.2). It has a number of advantages over alternative locations, chief of which is direct access by way of a major highway. The hydraulic geometry of the reach was previously examined by Rice (1979).

1.2 Local Geomorphology and Geology

1.2.1 Geomorphology

The Sunwapta River is proglacial with flow in the upper reaches being principally derived from melting of the Athabasca and Dome Glaciers. Proximal to these glaciers is an extensive outwash, degraded immediately downstream of Sunwapta Lake. This is due to restricted sediment supply as a consequence of sediment storage in this recently formed lake. The outwash is restricted at its downstream end by the Sunwapta Gorge. Local floodplain widening and channel braiding also occurs in the vicinity of the Stutfield Glacier outwash and alluvial fan. Downstream, the river is locally confined by a bedrock outcrop. However, subsequent to its emergence in the wide Beauty Creek flats area it forms a braided channel pattern.

Along the Beauty Creek flats the valley floor has a width of approximately 0.5 km and is bounded on the west side by wooded, steep-sided valley walls. On the east side the lateral extent of the valley train is presently restricted by Highway 93, although it formerly occupied the whole valley floor. The valley itself has a slightly sinuous form which is reflected in the orientation of the valley train (Fig 1.2).

A number of significant tributaries enter the river in the study area. On the west side the reach is joined by Wooley Creek and Diadem Creek (Fig 1.2). Wooley Creek has its source at the snout of a small cirque glacier and has formed a small alluvial fan which is now degraded. Diadem Creek, similarly, has a source in a high alpine cirque glacier and

FIG.1.1 LOCATION OF FIELD AREA

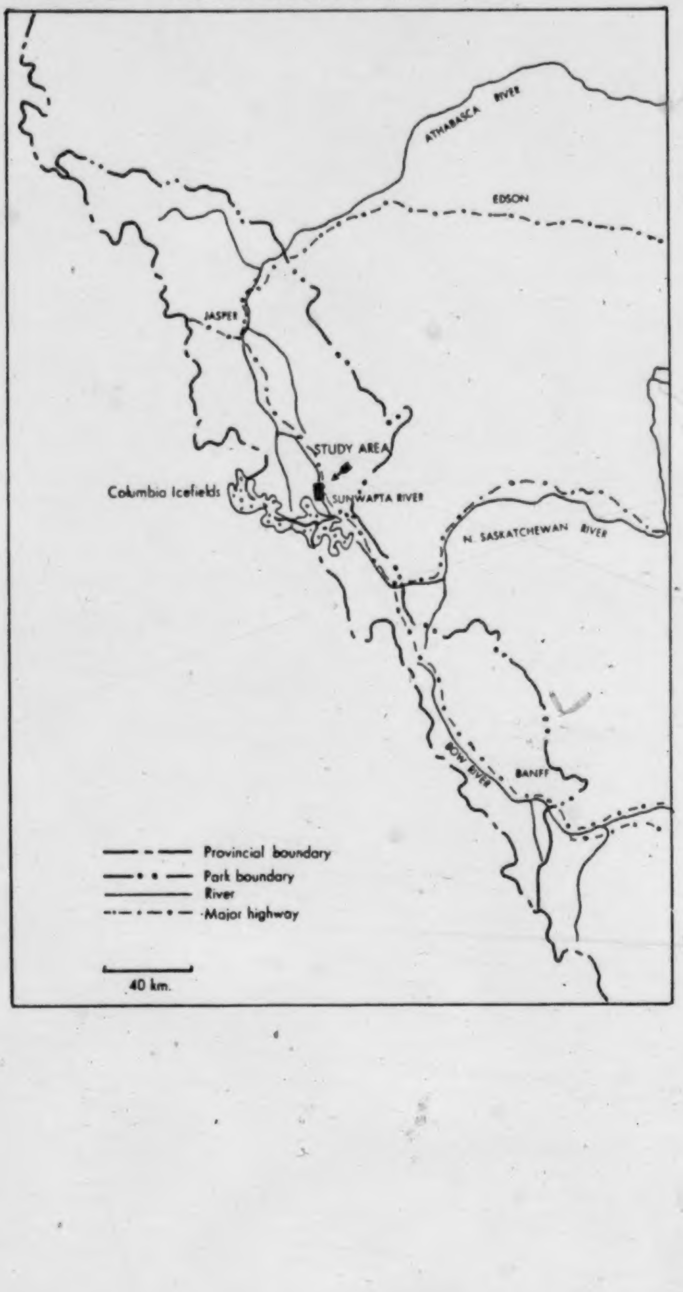
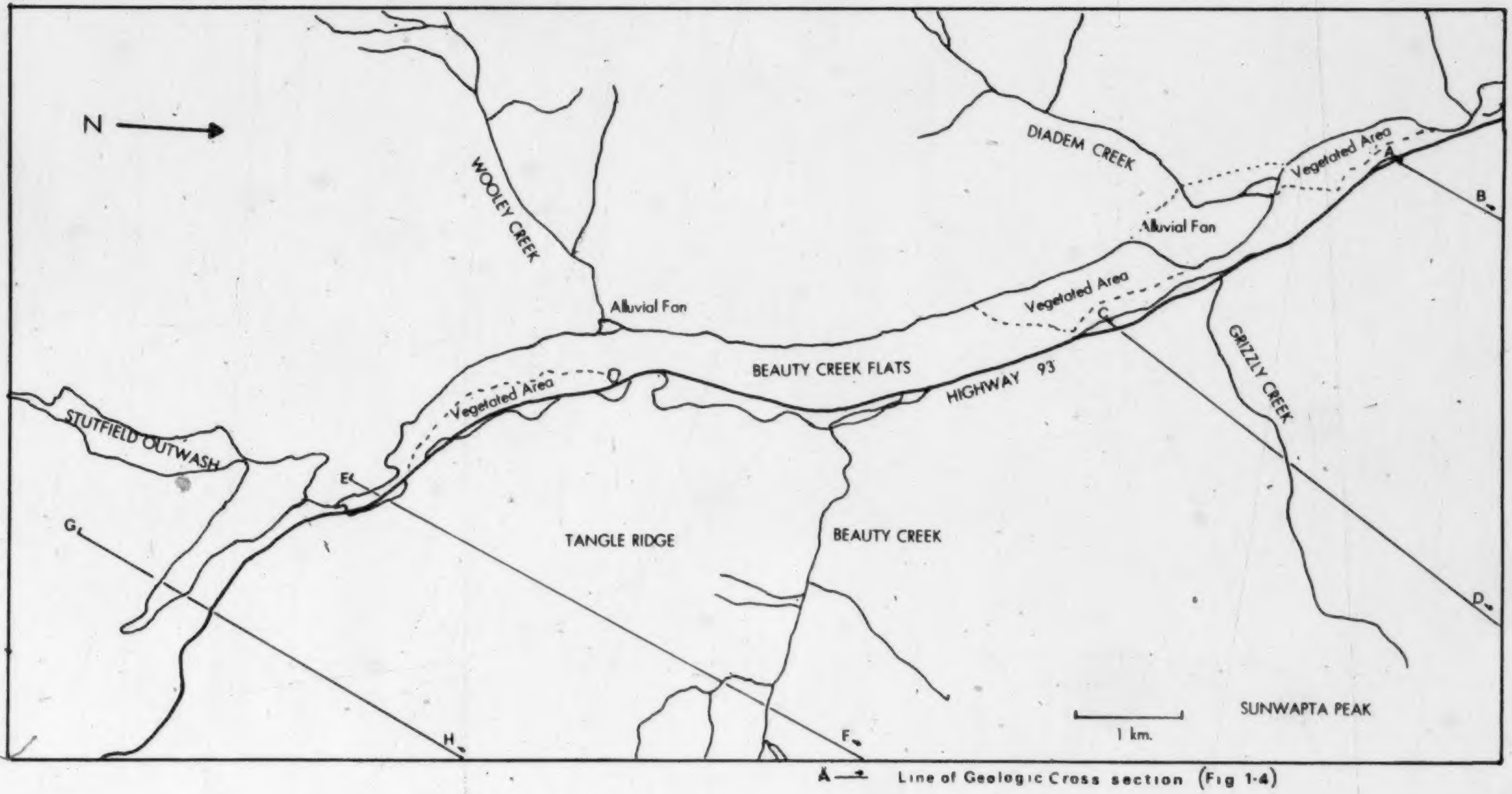

ATHABASCA RIVER
EDSON
JASPER
STUDY AREA
Columbia Icefields
SUNWAPTA RIVER
N. SASKATCHEWAN RIVER
BOW RIVER
BANFF
Provincial boundary
Park boundary
River
Major highway
40 km.

FIG. 1.2 BEAUTY CREEK FLATS


N
WOOLEY CREEK
DIADEM CREEK
Vegetated Area
Alluvial Fan
Vegetated Area
Alluvial Fan
BEAUTY CREEK FLATS
HIGHWAY 93
Vegetated Area
GRIZZLY CREEK
STUTFIELD OUTWASH
TANGLE RIDGE
BEAUTY CREEK
SUNWAPTA PEAK
1 km.
A
B
C
D
E
F
G
H

A → Line of Geologic Cross section (Fig 1-4) has constructed a large alluvial fan into the study reach. This fan forms a major obstruction restricting the river to a single channel and causing local changes in water surface slope, channel pattern and sedimentation. Highway construction, with the removal of gravel for borrow, has significantly altered the morphology of the fan and Diadem Creek has been diverted to its north side.

Two tributaries enter the study reach from the east. Beauty Creek derives its flow from a presently non-glacial upland catchment and enters the reach through large culverts under the highway. Observations showed that these pipes do not restrict sediment transport. Prior to highway construction, as shown by aerial photographs, the stream formed a separate braided sub-unit with a mid-reach confluence. Grizzly Creek also enters the reach through large diameter pipes. Its flow is derived from a small icefield on the north side of Sunwapta Peak and the channel is steep. This creek is currently aggrading a fan of coarse debris.

1.2.2 Geology

The only major study of the geology in the area was that by Hughes (1955) who investigated the area to the east of the field location, from Tangle Ridge in the south to the Endless Chain in the north. Earlier, less detailed investigations were carried out by Allan (1938) and Severson (1950).

Hughes (1955) suggested that the Beauty Creek flats lie within a single, synclinal, structural unit with an axis trending south-eastwards from Tangle Ridge through Nigel Peak and north-westwards towards the Sunwapta Falls. The axis of the structure, therefore, lies to the east of the river in what will be defined as the proximal and medial sub-reaches and to the west of the river in the lower reaches.

Hughes (1955) showed that the western limb of the structure dips steeply eastward at angles up to 75 degrees on Tangle Ridge. Similar dips occur on the western slopes of the Sunwapta River valley. He suggested that the east limb of the structure has a width of approximately 11 km, with an average dip of 25 degrees westwards, ranging from 9 degrees near the axis at Stanley Falls to 39 degrees on Sunwapta Peak. He also postulated the existence of a significant strike fault along the valley of Beauty Creek.

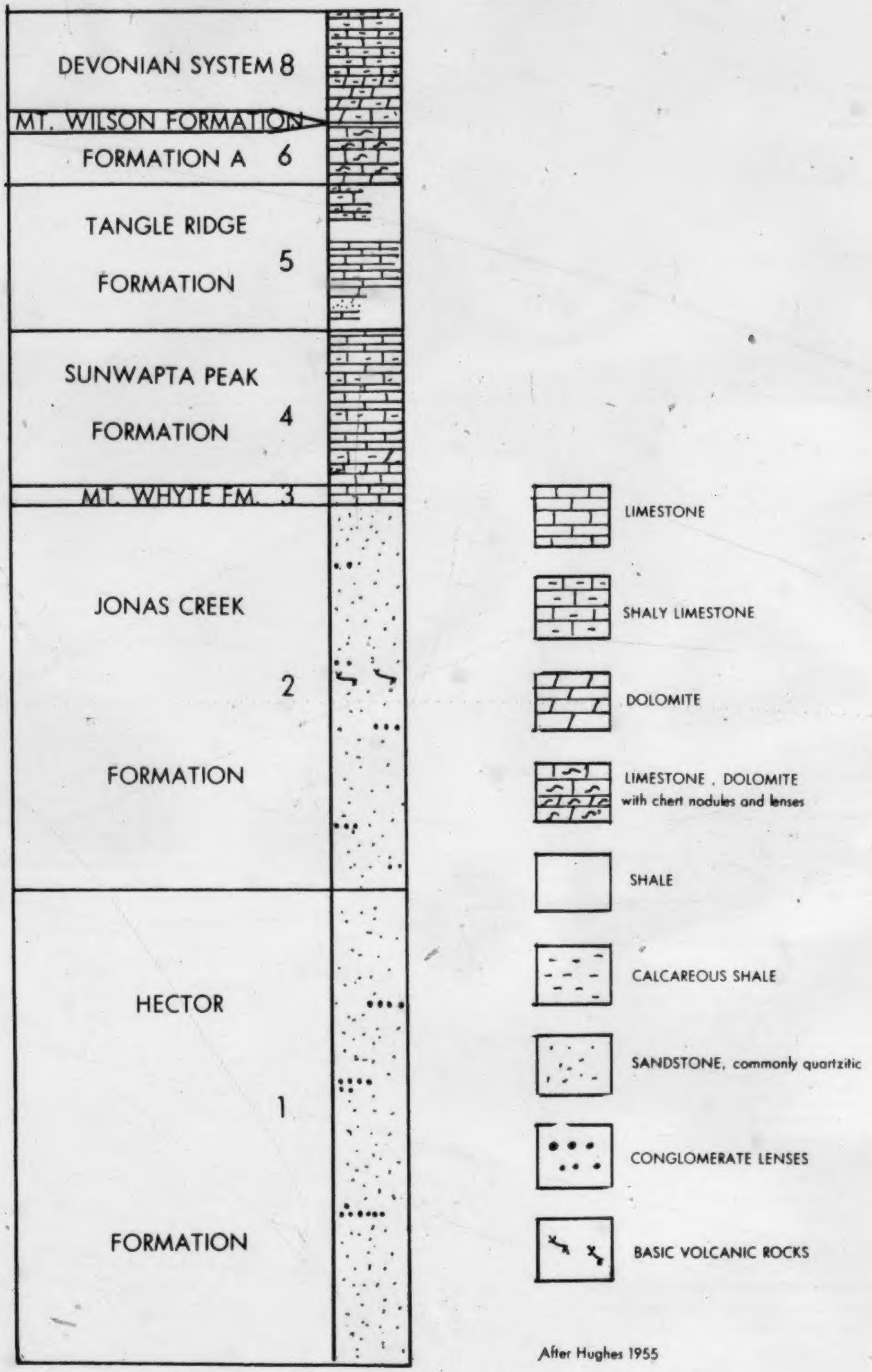
Hughes (1955) stated that strata of Pre-Cambrian, Cambrian, Ordovician and Devonian ages are present in the region (Figs 1.3 and 1.4). The Pre-Cambrian rocks have a thickness of approximately 3350 m and were subdivided by Hughes (1955) into the lower Hector Formation and the upper Jonas Creek Formation. The Hector Formation consists of green slatey shales, interbedded with pebble quartzites, conglomerates and sandstones (Hughes 1955). This formation is not exposed in the immediate vicinity of the field area, although the lithologies described for it are found in the river sediments. The Jonas Creek Formation was described by Hughes (1955) as having a thickness of approximately 1525 m. He found yellow quartzites, which become red and pink on weathering, local pebble bands and intercalated shale lenses. Mapping by Hughes (1955) indicated that the Jonas Creek Formation underlies part of the proximal reach of the study area.

The Cambrian strata were found to have a thickness of approximately 1430 m (Hughes 1955). The basal Cambrian formation, the Mount Whyte Formation, comprises a lower limestone and dolomite member, a middle green meta-argillite member and an upper oolitic limestone member. Within the study area, Hughes (1955) found exposures of the lower member on bedrock islands within the study reach, and middle and upper members on the west side of Tangle Ridge, at the foot of extensive cliffs.

Overlying the Mount Whyte Formation is the extensive Sunwapta Peak Formation comprising limestone, predominantly nodular although locally thin bedded or massive, and dolomite, cream-white in colour, pure to calcareous in nature (Hughes 1955). The formation is extensively exposed on Sunwapta Peak and underlies most of the study reach as well as being exposed along Beauty Creek. Baird (1977) stated that the Sunwapta Peak Formation is exposed along the cliffs and peaks to the west of the Sunwapta River. Allan (1938) noted that there are extensive exposures in cliffs on the west side of the upper outwash and on the north face of Mount Kitchener.

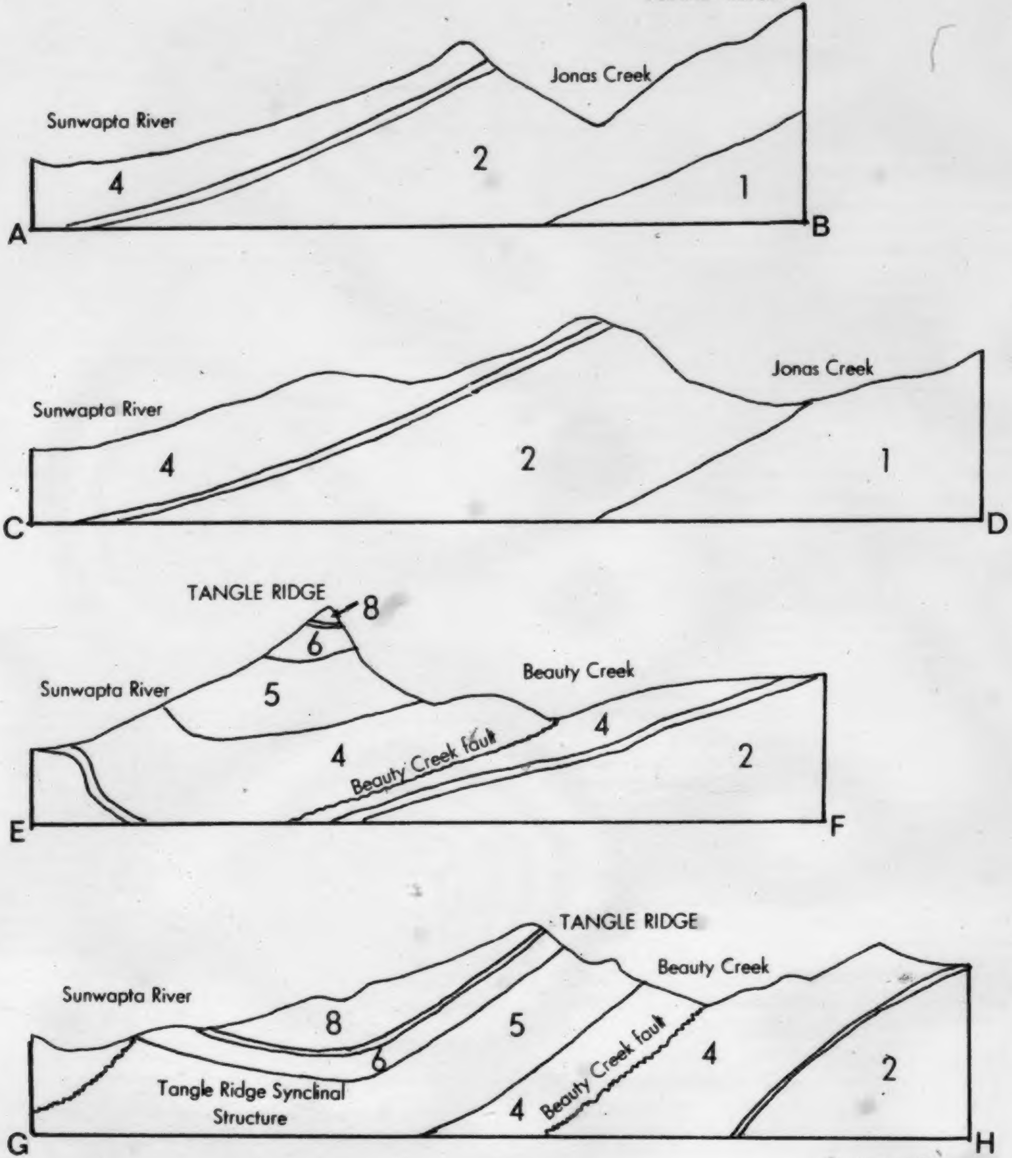
The Sunwapta Peak Formation is overlain by a sequence of shale and limestone beds, termed the Tangle Ridge Formation by Hughes (1955). This formation has a thickness of 580 m. Extensively exposed on Tangle Ridge the limestone is predominantly dense, buff, light brown or grey in colour and the shale is dominantly green in colour.

FIG. 1.3 GENERALISED STRATIGRAPHIC SECTION


DEVONIAN SYSTEM 8
MT. WILSON FORMATION
FORMATION A 6
TANGLE RIDGE FORMATION 5
SUNWAPTA PEAK FORMATION 4
MT. WHYTE FM. 3
JONAS CREEK FORMATION 2
HECTOR FORMATION 1
LIMESTONE
SHALY LIMESTONE
DOLOMITE
LIMESTONE, DOLOMITE with chert nodules and lenses
SHALE
CALCAREOUS SHALE
SANDSTONE, commonly quartzitic
CONGLOMERATE LENSES
BASIC VOLCANIC ROCKS

After Hughes 1955

FIG. 1. 4 STRATIGRAPHIC CROSS-SECTIONS


JONAS RIDGE
Jonas Creek
Sunwapta River
4
2
1
A
B
Sunwapta River
Jonas Creek
4
2
1
C
D
TANGLE RIDGE
8
6
5
Sunwapta River
Beauty Creek
4
Beauty Creek fault
4
2
E
F
TANGLE RIDGE
Beauty Creek
Sunwapta River
8
6
5
Beauty Creek fault
4
2
Tangle Ridge Synclinal Structure
4
G
H

After Hughes 1955

Horizontal and Vertical Scales 1 inch to 1 mile

Both Severson (1950) and Hughes (1955) reported the existence of two Ordovician formations in the area. The lower one, Formation A (Hughes 1955), comprises approximately 230 m of grey limestones with black chert nodules, minor green shale lenses and conglomerate bands. Overlying this is a white quartzitic sandstone formation, the Mount Wilson Formation, which thins in a northward direction (Severson 1950).

Silurian and, more extensive, Devonian rocks are exposed adjacent to the higher reaches of the Sunwapta River (Severson 1950) and to a limited extent on top of Tangle Ridge (Hughes 1955). The Silurian is represented by a massive grey dolomite bed. The Devonian beds consist predominantly of limestone, with the extensive, massive, grey, Palliser Formation (approximate thickness 580 m) overlying the thinly bedded, black, limestone, Fairholme Formation and underlying less extensive, black, Exshaw limestone and shale beds (Severson 1950). There is a limited exposure of Banff shale, of Mississipian age, on Nigel Peak (Severson 1950).

1.3 Channel Pattern

Channel patterns change over the reach in a similar manner to those reported from other studies. (Krigstrom 1962, Fahnestock 1969, Smith D.G. 1971, Bradley *et al.* 1972.) Four sub-reaches were defined to facilitate the description of the channel patterns in the study reach and to assist in the subsequent statistical analysis of sediment variations.

1) The proximal sub-reach lies between the upstream end of the Beauty Creek flats and the Wooley Creek fan.

2) The medial sub-reach occurs downstream from Wooley Creek and extends to Beauty Creek.

3) The distal sub-reach lies between Beauty Creek and the Diadem Creek fan.

4) The inter-fan sub-reach begins downstream of the Diadem Creek fan and terminates at the fan of the unnamed creek.

1.3.1 Proximal sub-reach

Upon emergence onto the Beauty Creek flats, the Sunwapta River is confined to the east by a large groyne and currently maintains a nearly straight course (Fig 1.5). The channel is incised approximately one metre below a gravel terrace and westward migration is taking place. The river continues as a single channel for about 400 m before braiding commences with the development of large bars (Fig 1.6). Local water surface slopes in this area are high and topographic differences between bar and water surfaces may be relatively great, up to 60 cm (Fig 1.7).

The main channel is sinuous with few braids for much of the proximal reach where it follows the western edge of the valley train. At high stages, a small number of distributaries branch from the main channel a short distance downstream from the initial braid (Fig 1.8). These carry flow along the eastern edge of the active surface and rejoin the main channel further downstream. As no further distributaries form in the next 2 km downstream it is probable that the valley surface has an east to west transverse slope. This contention is supported by the existence of an extensive area of vegetated gravel occupying approximately one half of the valley flat width. This low terrace is at a height of about 50 cm above the active gravel area. Cross-profiles surveyed by Rice (1979) also indicate a general east to west slope to the valley flat in this area.

Approximately 500 m upstream of the Wooley Creek fan the river divides into a number of minor channels, delimited by small longitudinal bars and highly active, large flats (Figs 1.9, 1.10). The change in channel pattern corresponds to a reduction in slope upstream of the fan.

1.3.2 Medial sub-reach

Adjacent to the Wooley Creek fan, and a bedrock outcrop, the flow combines to form a single main channel (Fig 1.11). Downstream this single channel is maintained although considerable lateral shifts in the position of the channel have created a large, complex gravel flat (Fig 1.12). Approximately 500 m downstream of the Wooley Creek fan, corresponding to an increase in the width of the valley flat, an area of flow expansion occurs. Variable deposition in this area controls the direction of flow in a 1.5 km long downstream reach (Fig 1.13). The single main channel divides into two systems,

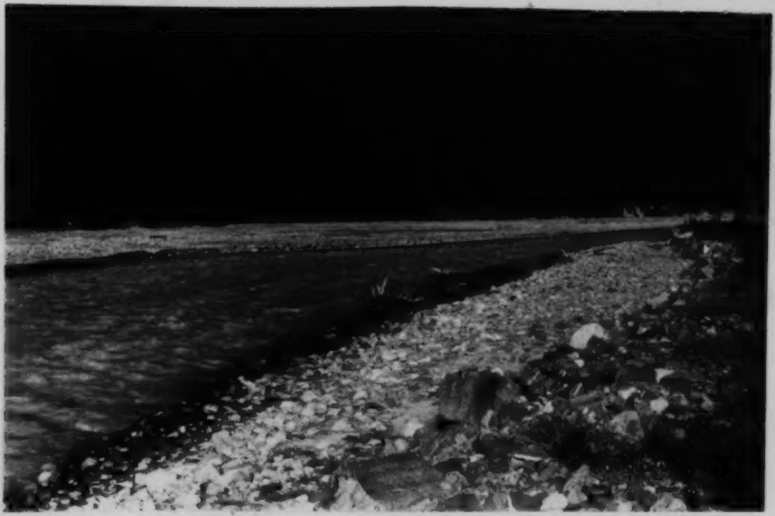


Figure 1.5 Single Channel, Proximal Sub-reach. (View downstream).

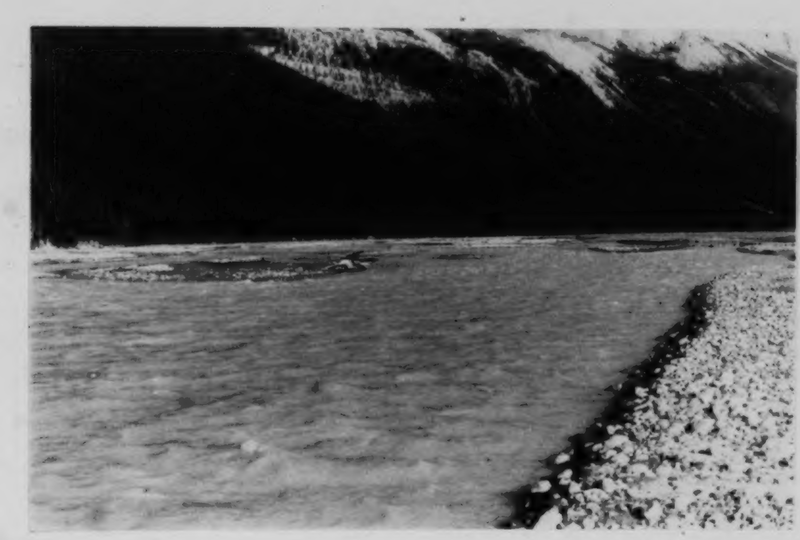


Figure 1.6 Initial Braid, Proximal Sub-reach. (View downstream).

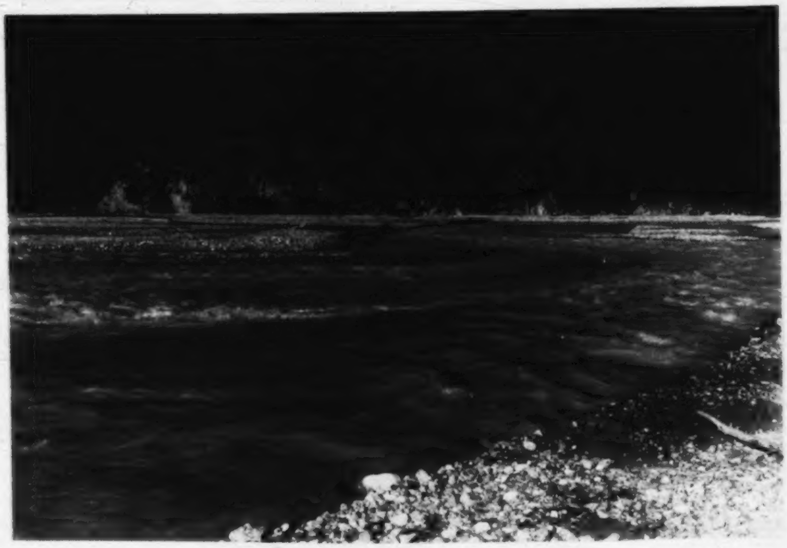


Figure 1.7 High Gradient Channel and Associated Bars, Proximal Sub-reach. (View downstream).

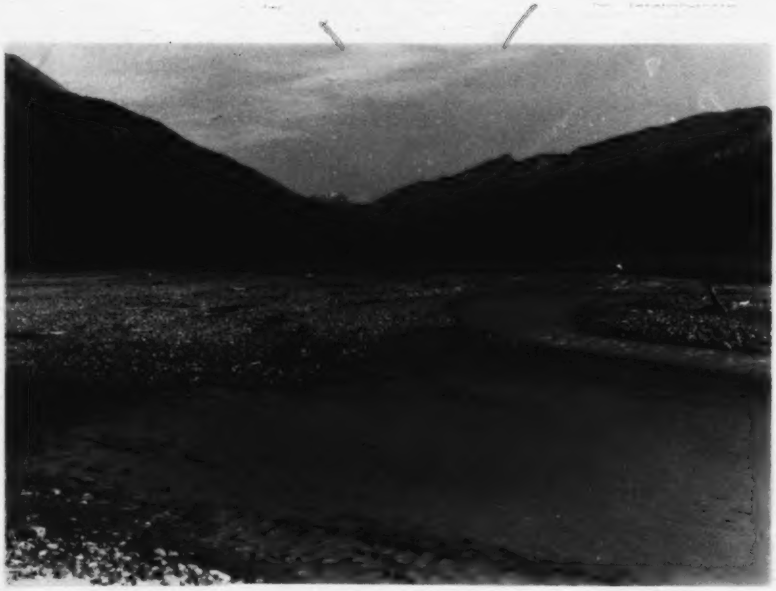


Figure 1.8 Minor Channel, East-side of Proximal Sub-reach. (View downstream). Abandoned gravel area appears to the right of the picture.

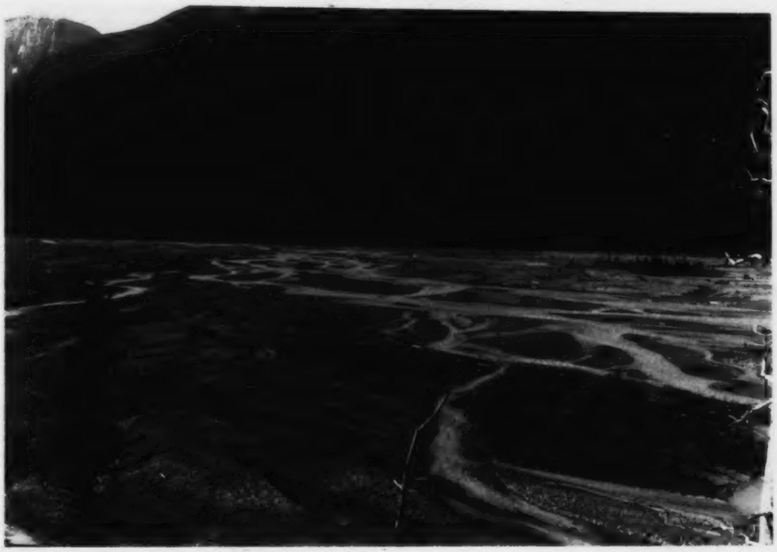


Figure 1.9 Braided Pattern Upstream of Wooley Creek (View upstream).

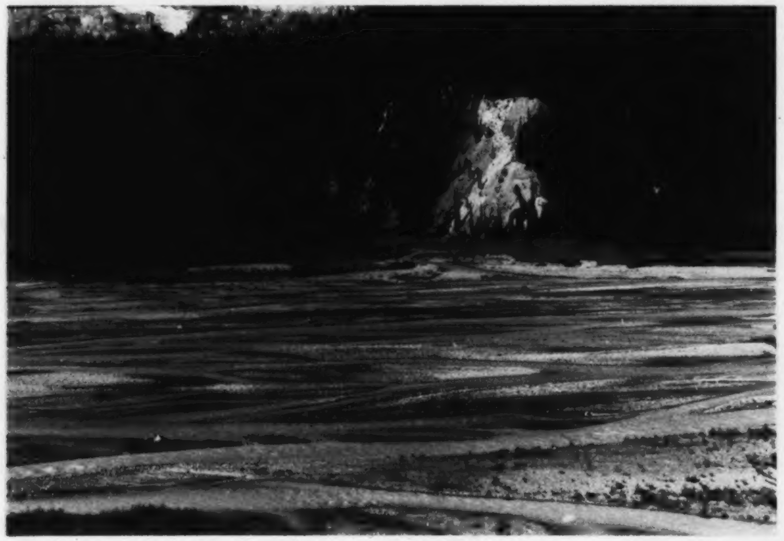


Figure 1.10 Wooley Creek Alluvial Fan (Flow left to right).
Note the abandoned nature of the fan surface.

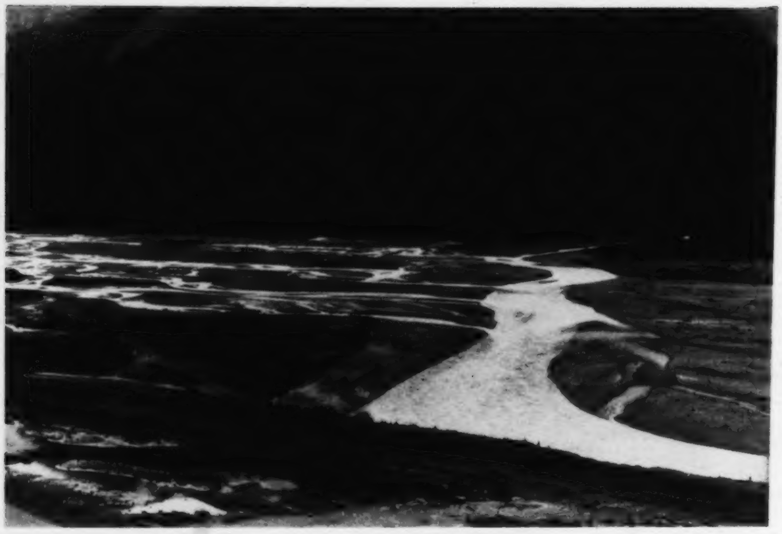


Figure 1.11 Single Channel Downstream of Wooley Creek (Flow towards viewer).

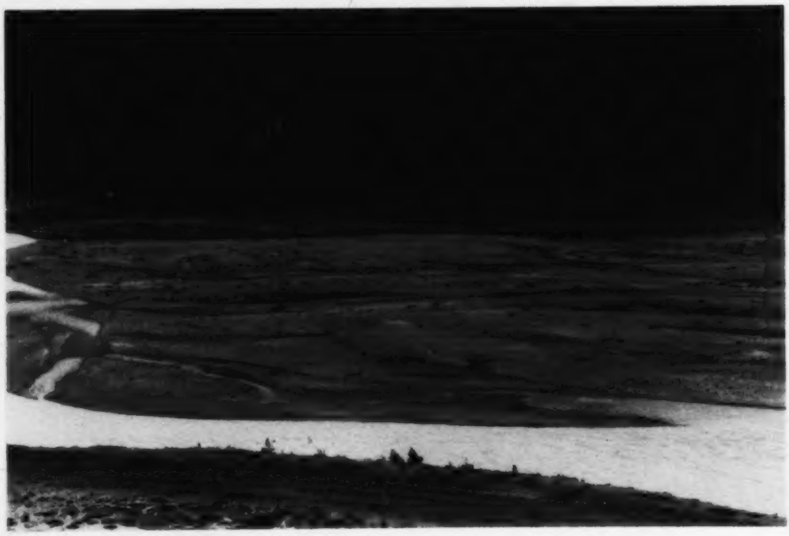


Figure 1.12 Large Complex Gravel Flat Downstream of Wooley Creek
(Flow from left to right).

separated by a large, partly stablised, vegetated area. The flow alternated between the two systems during the period of field observation with only one being dominant at a single time.

The west system, when dominant, comprises a single main channel with numerous, small, in-channel bars. The east system (Fig 1.14), at the time of observation, was actively modifying former channels on the stabilised gravel flat area. The upstream portions of this system had been extensively altered, with the development of large, longitudinal depositional flats. Downstream, in the distal area of the east system erosional remnants of the stabilised area defined the channel pattern.

Approximately 1.5 km above Beauty Creek the flow converges into a single dominant channel, which closely parallels the highway (Fig 1.15). Flow impingement upon the highway causeway is prevented by a series of oblique groynes. Depositional forms tend to be more markedly oblique and transverse to the flow as compared to those of upstream areas. Accretional areas tend to show less variation in relief as compared to those of upstream areas, and at high stage these flats are largely inundated. At lower discharges flow is confined to small channels, which delimit longitudinally orientated flats (Figs 1.16, 1.17).

To the west side of the dominant channel, a large , partly vegetated, area of gravel has developed as a result of lateral accretion. A number of minor channels which cross the area appear to be largely stable. Between the groynes, adjacent to the highway, there are a number of large splays, which result from gravel deposition into these inter-groyne areas. Immediately upstream of its confluence with Beauty Creek the main channel system has a large splay which is active at high flow. This may be a response to a reduction in the water surface slope, related to the backwater created by the large groyne which protects the Beauty Creek culvert (Fig 1.18). At low flow the area is characterised by longitudinally orientated, complex flats.

1.3.3 Distal sub-reach

In the distal reach the main channel and the Beauty Creek tributary are separated initially by a large groyne, the main channel being deflected away from the highway causeway. In-channel deposition is limited to small, longitudinal gravel flats but

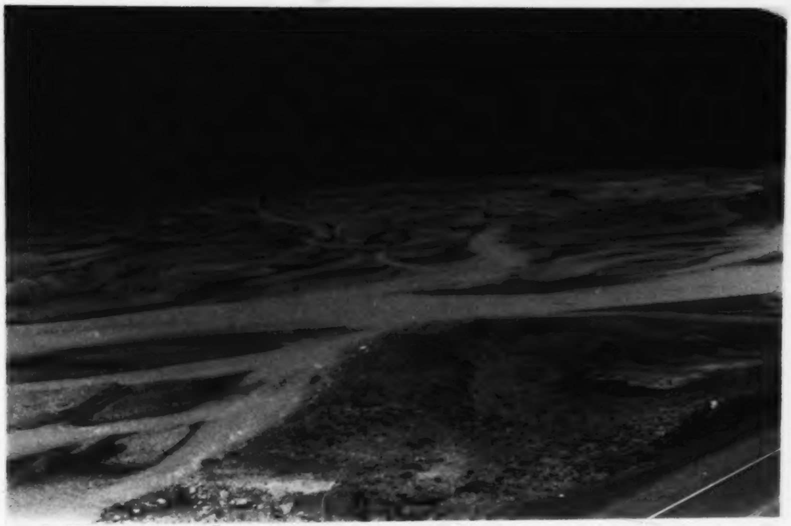


Figure 1.13 Area of Flow Expansion, Medial Sub-reach (View downstream).

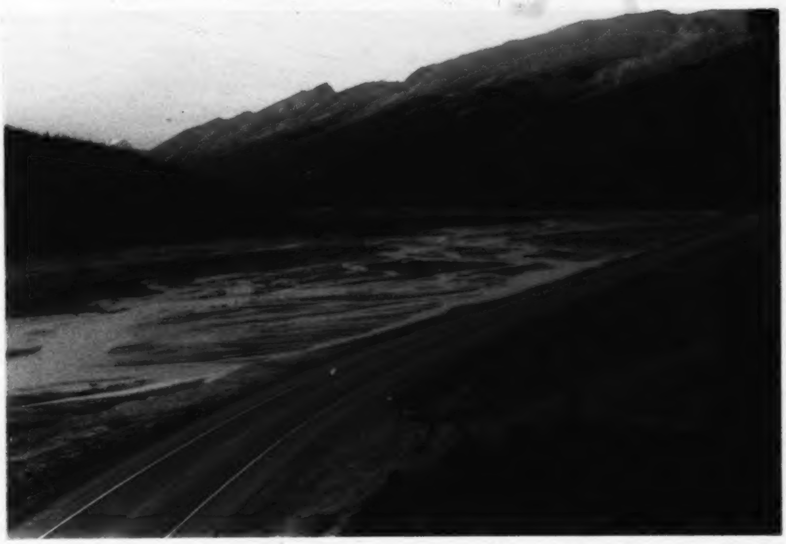


Figure 1.14 East Channel System, Medial Sub-reach (View downstream).
Note the partly vegetated area to centre of the reach.

Figure 1.15 Convergence of Flow, Medial Sub-reach. (View upstream).

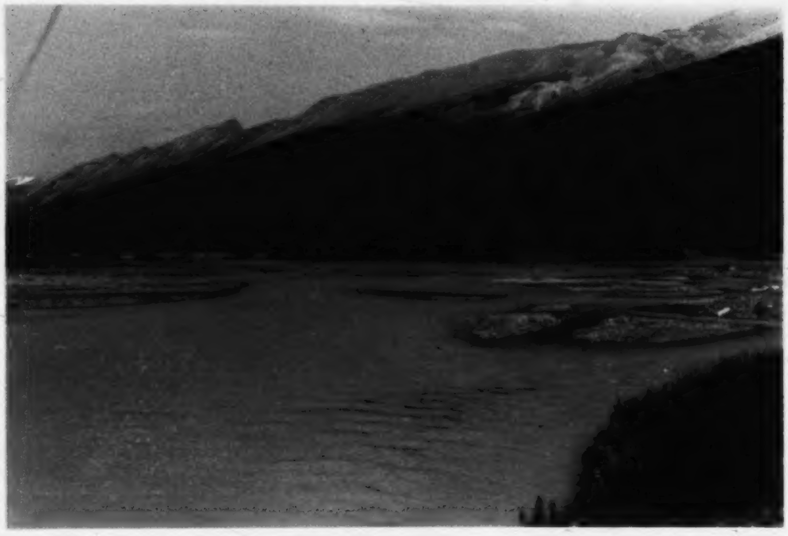


Figure 1.16 Main Channel System, Downstream End of Medial Sub-reach (View downstream).

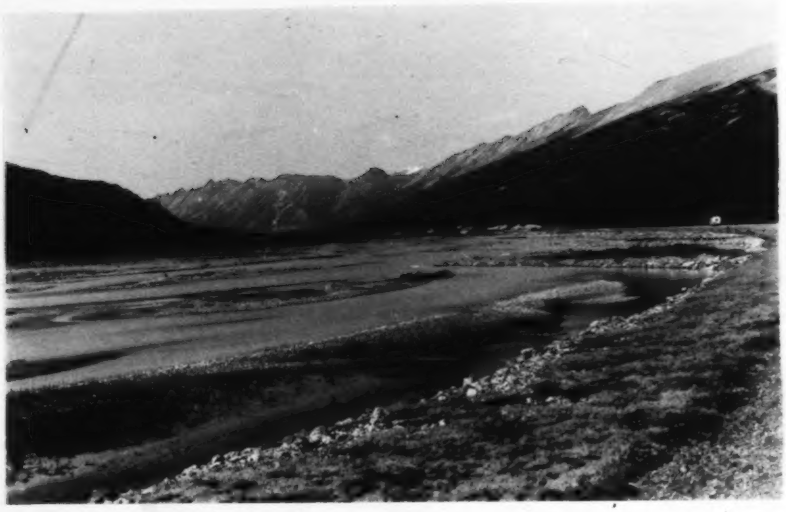


Figure 1.17 Main Channel System, Downstream End of Medial Sub-reach (View downstream). The groynes extend from the highway causeway (right of picture).

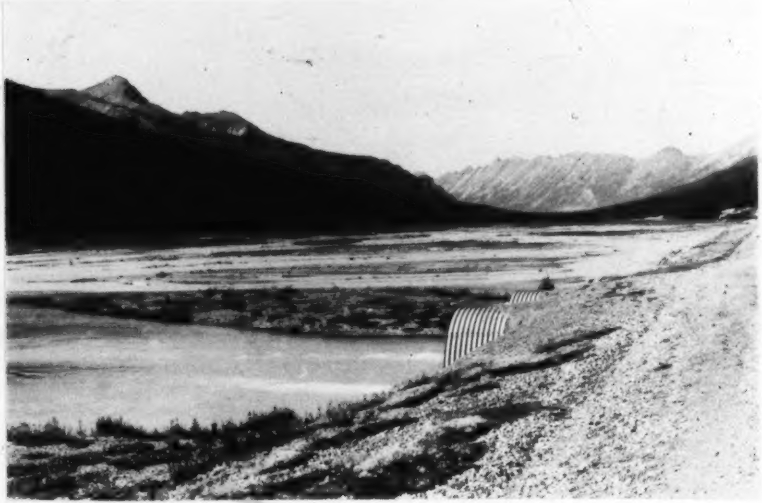


Figure 1.18 Confluence of Beauty Creek and Sunwapta River (View downstream). Note the splay form in centre reach, beyond the partly vegetated gravel bank.

immediately downstream of the groyne flow diverges and deposits large sheets of gravel towards the highway (Fig 1.19). Flow from Beauty Creek, with additions from the main channel, parallels the highway causeway before being deflected towards the main channel by another groyne. Gravel deposition occurs at this point in a splay form. At high stages the gravel flats and splays are largely submerged (Fig 1.20).

Approximately 1 km downstream of Beauty Creek, the main channel divides into multiple, small channels, although a dominant channel occurs along the west side of the reach (Figs. 1.21 and 1.22). The channels delimit a number of small braid bars which are partially vegetated and carry large amounts of drift wood. Certain areas are relict with large, partly stablised, vegetated flats and small vegetated islands. This channel pattern represents a transition between the highly active braided system upstream and a more stabilised pattern downstream and occurs in an area where the water surface slope shows a marked decline in comparison to upstream areas.

This transitional pattern grades abruptly into a short anastomozed reach, similar to those described by Smith D.G and Smith N.D. (1981) (Fig 1.23). The area is dominated by large, vegetated islands which are stable and are bordered by low levees. The islands receive only overbank sediment deposited at very high stages. The upstream and lateral margins are being eroded, but downstream accretion is occurring and forms partly stablised sand and gravel areas (Fig 1.24). The channels have variable widths between the vegetated islands. Flow diverges into the wider areas where large lobate bars of gravel and sand develop.

This channel pattern is succeeded downstream by a sandy braided section extending approximately 1.5 km to the Diadem Creek fan (Fig 1.25). There is a large vegetated area to the west which receives overbank deposits at very high stages. At its northern end silt and sand deposits are derived from the Diadem Creek fan. Within the channel there are a number of bar forms and depositional units similar to those described by Cant and Walker (1978).

A hierarchy of in-channel forms is recognisable. The largest feature is a large, partly vegetated island which is accreting at the upstream and downstream margins. This island is being attached to the adjacent west bank by the infilling of a small slough channel. A similar, but less stabilised, island emerges at low stages further downstream

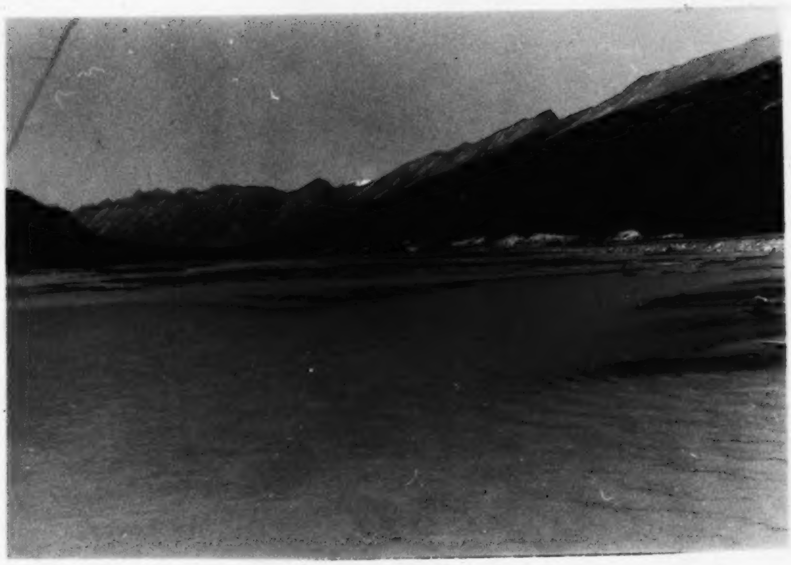


Figure 1.19 In-Channel Deposition, Downstream of Beauty Creek (View downstream).

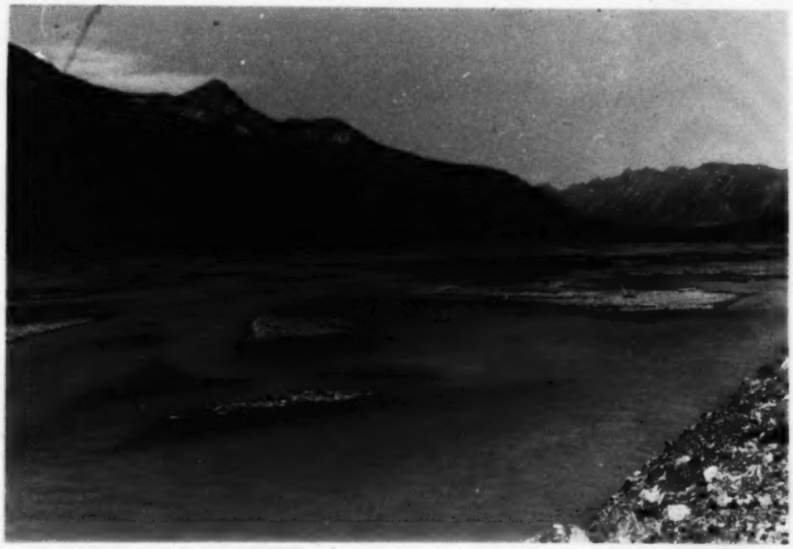


Figure 1.20 In-Channel Deposition, Distal Sub-reach (View downstream).

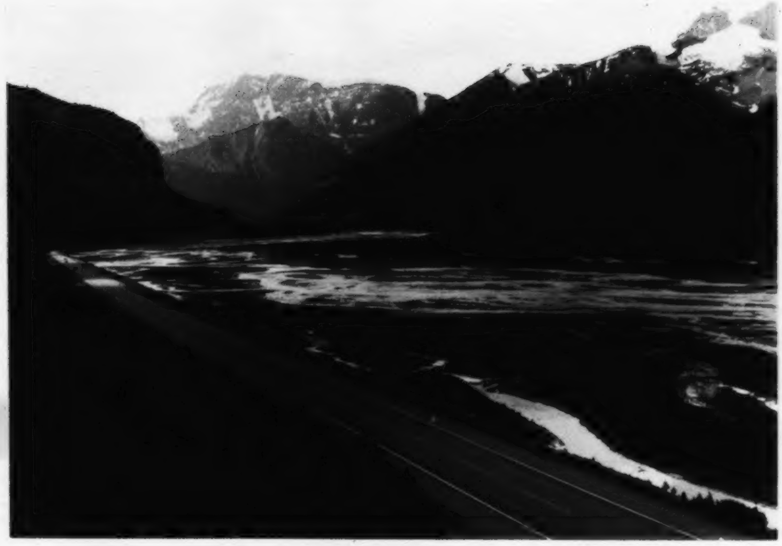


Figure 1.21 Elevated View of Medial and Distal Sub-reaches (View upstream).

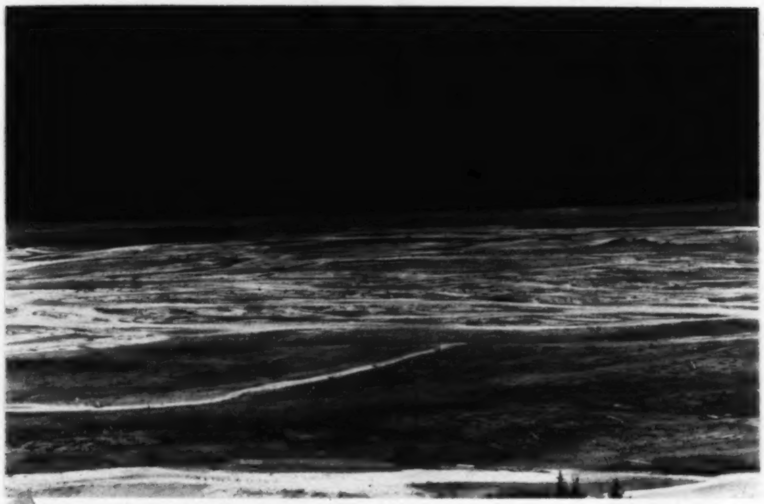


Figure 1.22 Transition Section, Distal Sub-reach (Flow from left to right).
Note the small multiple channels and sinuous bar forms.

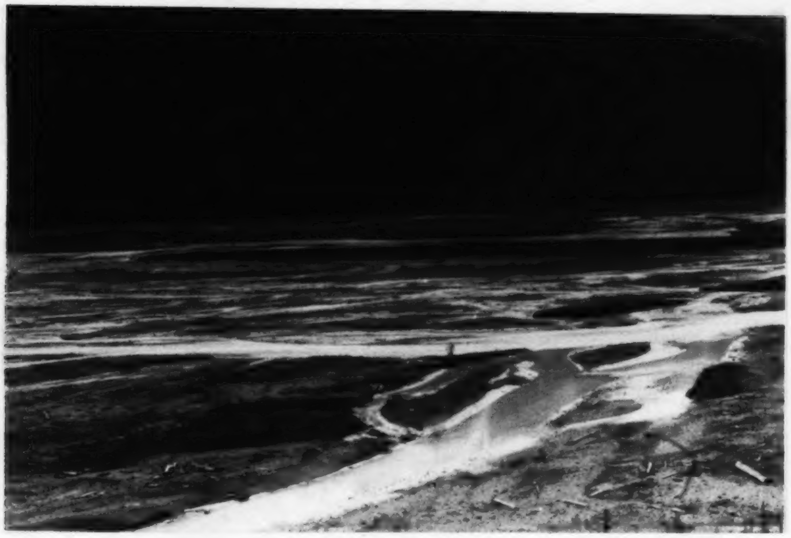


Figure 1.23 Anastomosed Section, Distal Sub-reach (Flow from left to right).

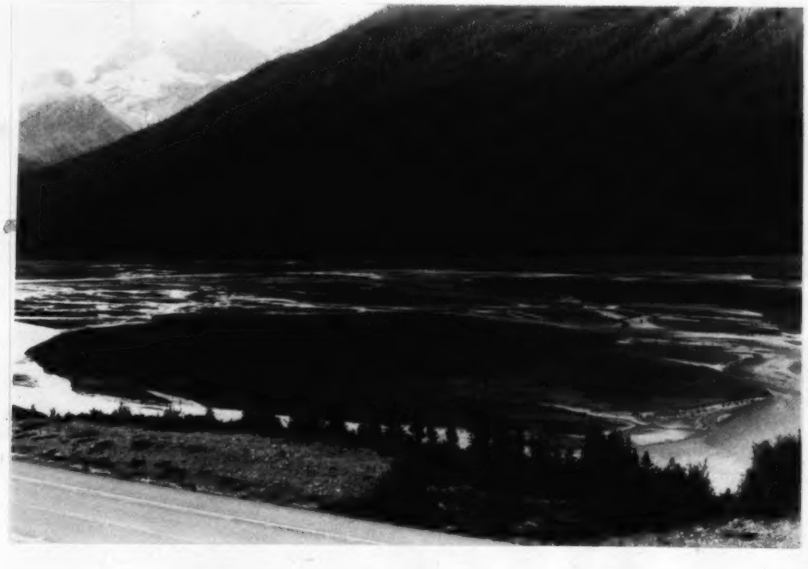


Figure 1.24 Anastomosed Section, Distal Sub-reach (View upstream).
Note the vegetated nature of the well-stabilised islands in the reach.

in the section (Fig 1.26). This is attached to the bank and is cut by transverse channels and scours. In large flow divergences mid-channel longitudinal bars with a downstream extent of 150 m occur (Fig 1.27). These are crescentic in shape, and develop downstream from triangular nuclei. From these nuclei a series of "horns" (Cant and Walker 1978) developed, extending curvilinearly downstream. Overlapping lobes developed adjacent to these bars and in other minor flow divergences. These have extensive avalanche faces forming into deeper water.

1.3.4 Inter-fan sub-reach

Flow is confined to a single channel, adjacent to the Diadem Creek alluvial fan, with local divisions occurring around stabilised and possibly artificially constructed bar complexes (Fig 1.28). At the initial flow constriction there is a marked break in the water surface slope (Fig 1.29). The flow divides, downstream of the fan into two main channels and a number of minor channels. Inter-channel areas are made up of stabilised gravel with sparse vegetation (Figs. 1.30 and 1.31). The size of the stabilised gravel areas increases downstream and the vegetation upon them becomes more dense (Fig 1.32). During observed high flows the pattern remained stable with gravel transport and deposition being confined to the channels. The two channels converge approximately 1km downstream and, corresponding with a marked decrease in slope, the reach adopts a sandy braided form similar to the section above the Diadem Creek alluvial fan (Figs. 1.33 and 1.34). Flow is largely confined to the eastern part of the valley floor by a large vegetated area of overbank sediment.

1.4 Slope Characteristics

The profile of the reach was surveyed by Rice (1979) with an additional survey of the lower inter-fan reach being obtained in conjunction with the current study (Ashmore: personnal communication). In both cases a water surface profile was obtained for the main channel. The slope profile demonstrates a concave-upwards form, although with a number of significant deviations from the widely described exponential form (Shulits 1941) (Fig 1.35).

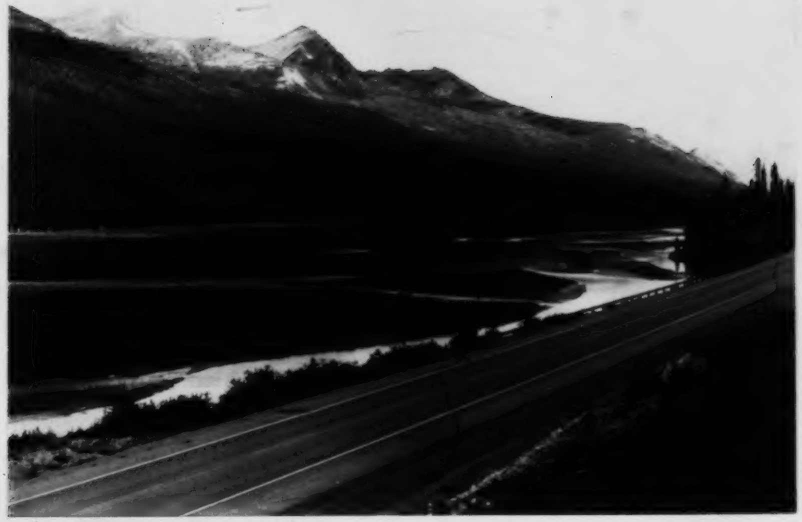


Figure 1.25 Upstream Portion of Sandy Braided Section, Distal Sub-reach. (View downstream).

Note the stabilised nature of the areas adjacent to the channels.

Figure 1.26 Sand Flat, Sandy Braided section, Distal Sub-reach. (Flow from left to right).

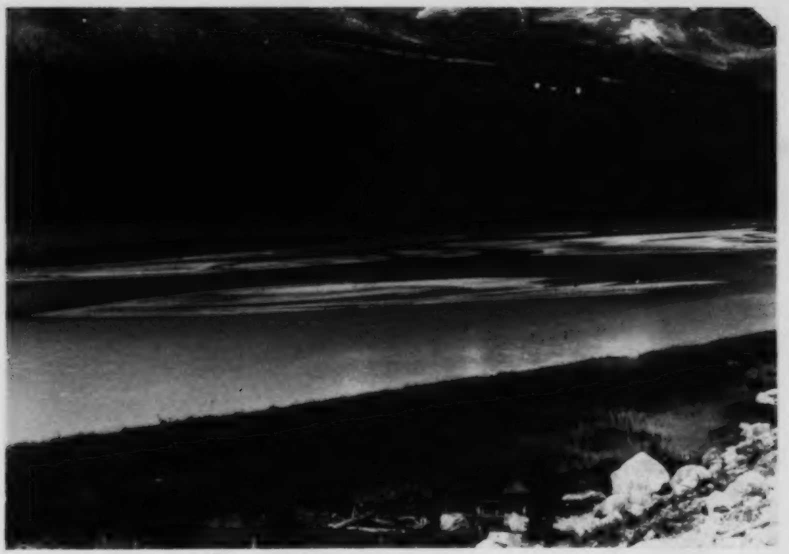


Figure 1.27 Longitudinal Bar, Sandy Braided Section, Distal Sub-reach (Flow from left to right).
Note the "horns" extending away from the bar head.

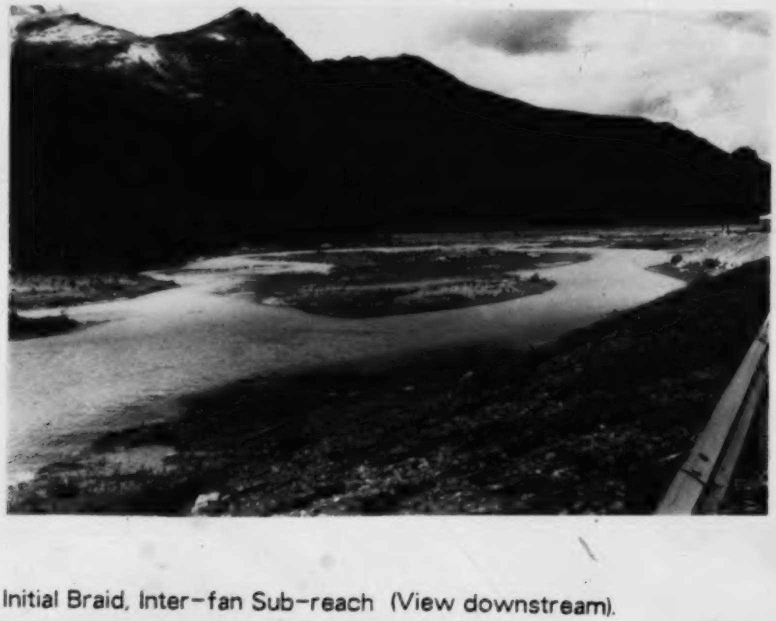


Figure 1.28 Initial Braid, Inter-fan Sub-reach (View downstream).
The Diadem Creek fan is to the left of the picture.

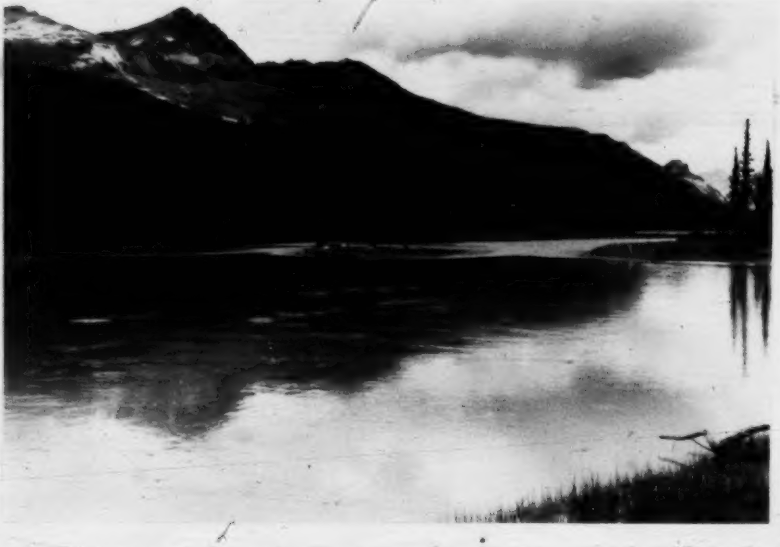


Figure 1.29 Break in Water Surface Slope at Diadem Creek. (View downstream).

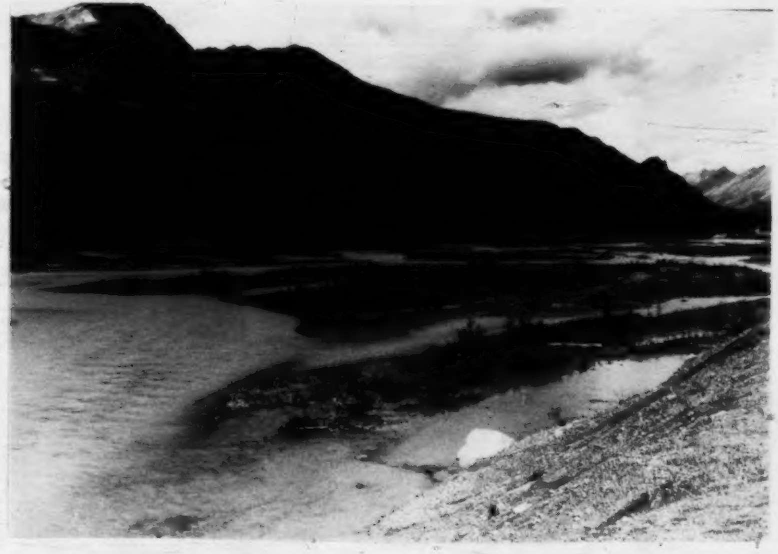


Figure 1.30 Inter-channel Gravel Areas, Inter-fan Sub-reach. (View downstream). Note the partly vegetated surface of the bars.

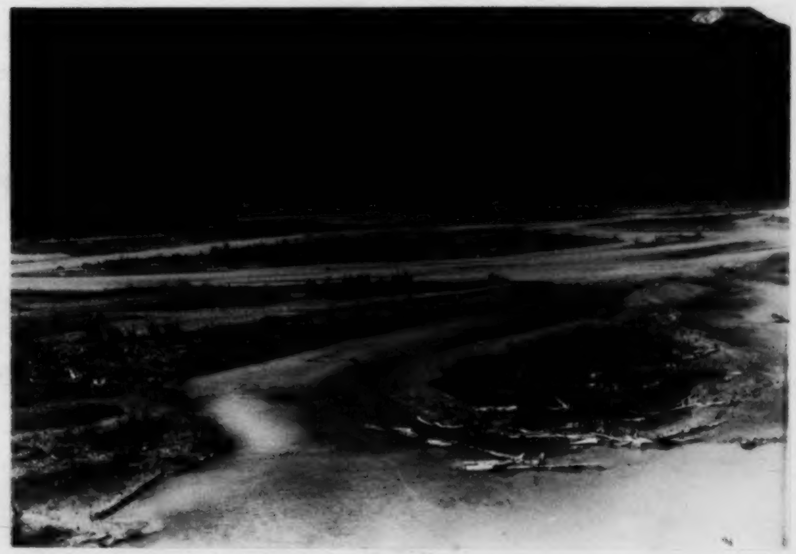


Figure 1.31 Inter-channel Gravel Area, Inter-fan Sub-reach. (View downstream).

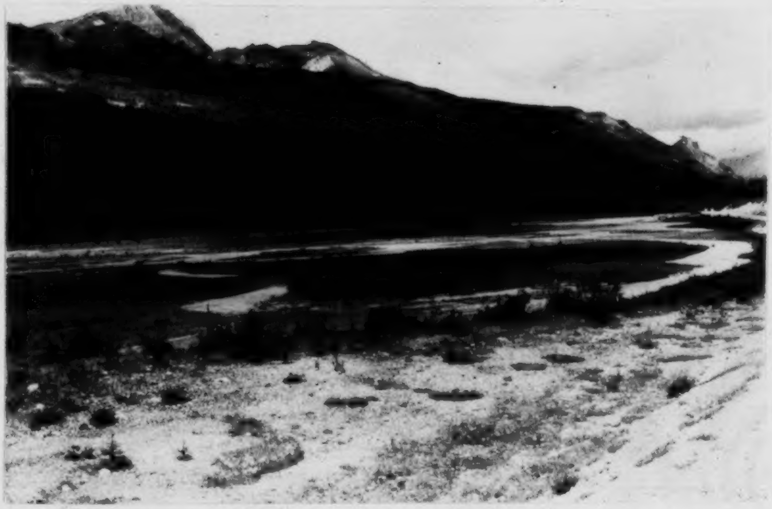


Figure 1.32 Well Stabilised Gravel Area, Inter-fan Sub-reach (View downstream). Note the increased density of vegetation on the bar surfaces as compared to the previous two photographs.

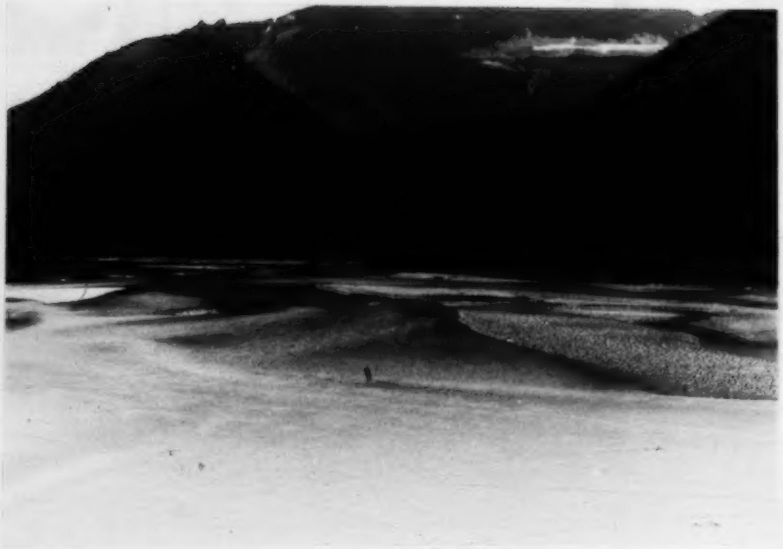


Figure 1.33 In-channel Deposition, Sandy Braided Section, Inter-fan Sub-reach (View upstream).

Note the transverse bar aggrading into the channel in the foreground.

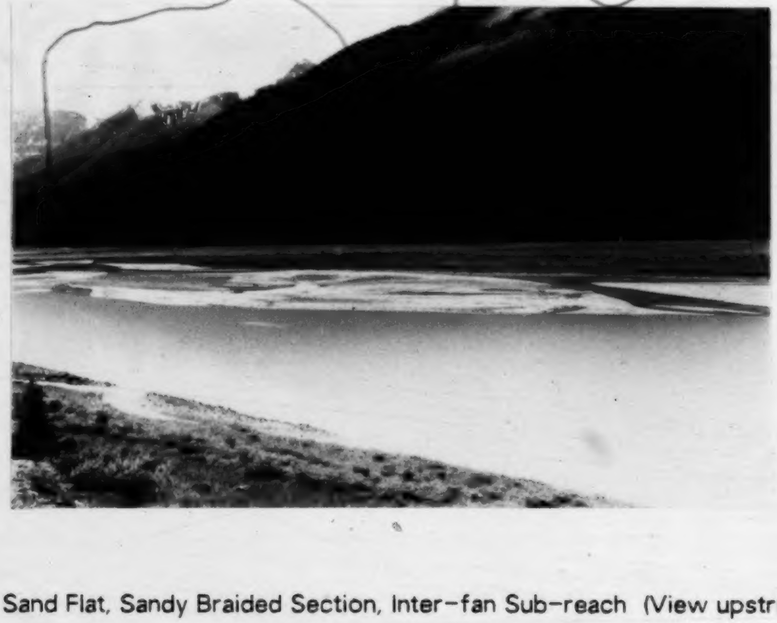


Figure 1.34 Sand Flat, Sandy Braided Section, Inter-fan Sub-reach (View upstream).

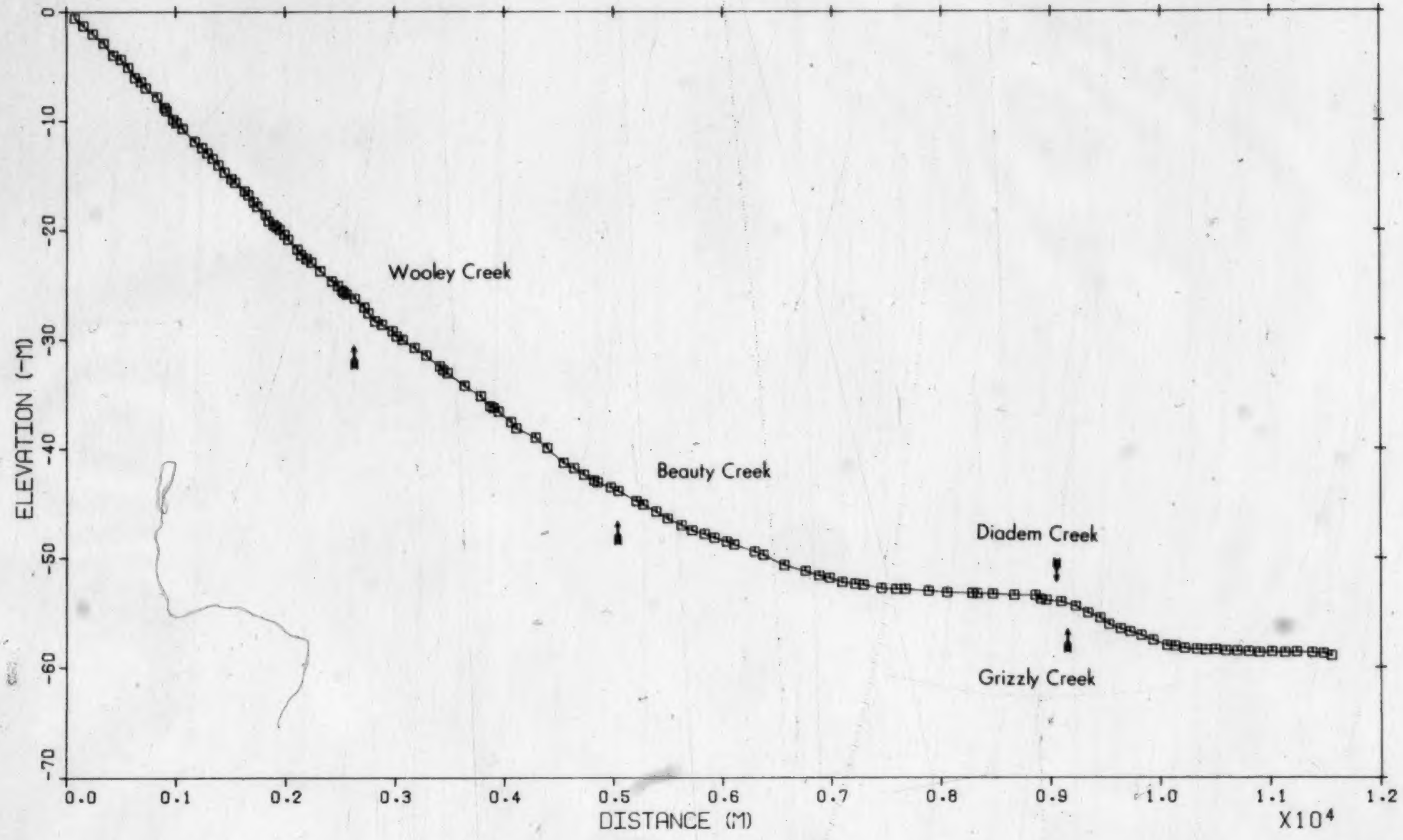


FIG. 1.35 WATER SURFACE PROFILE

The proximal sub-reach generally shows a constant slope with a significant decrease in gradient only occurring upstream of the Wooley Creek fan. The slope in the single channel section of the proximal reach is slightly less than in the braided section immediately downstream. Although local steepening occurs downstream of the Wooley Creek fan, a general decline in slope occurs in the medial and distal sub-reaches. However, there is a local decrease in slope upstream of the confluence of Beauty Creek and the main reach. There is a local increase in water surface slope downstream of this confluence.

The Diadem Creek alluvial fan forms a local base level for the upper parts of the reach, with the associated backwater curve extending upstream for approximately 1.7 km. There is a marked break of slope and a steepening of gradient adjacent to the fan The gradient increases downstream of Grizzly Creek, where the reach adopts a constant slope for approximately 1200 m. At this point, corresponding to the downstream limit of gravel bed material, there is a marked decline in slope related to the backwater created by the alluvial fan downstream.

There is a broad similarity between the observed changes in channel pattern and slope and those described by Smith D.G. (1971) for the North Saskatchewan River. He ascribed the changes in channel pattern of the North Saskatchewan River to aggradation up and downstream of active alluvial fans.

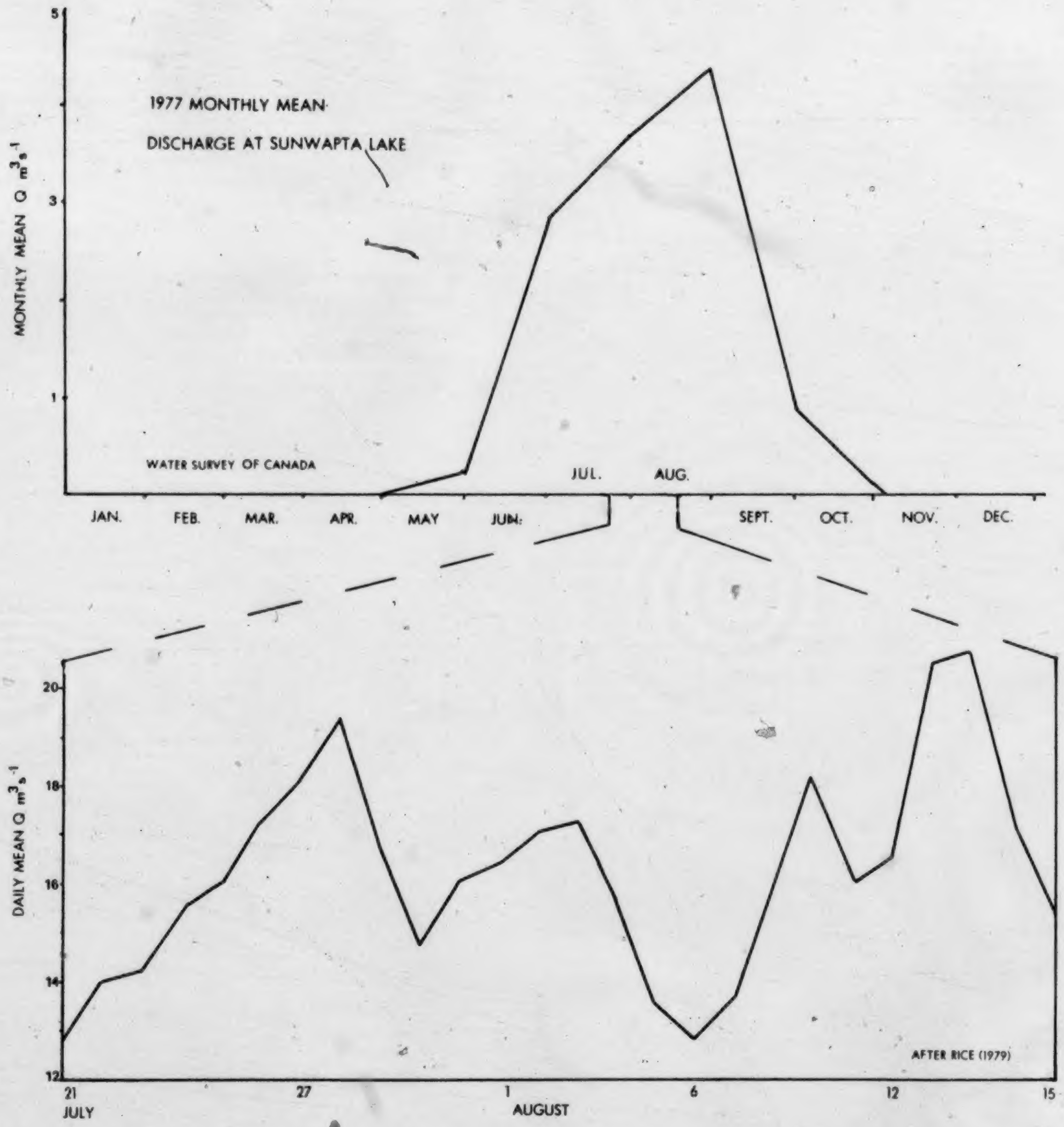
1.5 Hydrology

In a previous study Rice (1979) showed that the discharge in the upper part of the Sunwapta River is controlled by glacier and snow melt. He contended that there were two annual discharge peaks, corresponding to the spring melt in April and May and to glacier melt during warm summer weather in July and August. Figure 1.36a shows monthly mean discharge for 1977 at the gauging station upstream of the Beauty Creek flats at Sunwapta Lake. Peak monthly discharges occurred during August and there were no high flows during the early spring of that year. During this investigation high flow was observed in July and August. This seemed to be related to three factors.

1) Snowmelt at high altitudes.

2) Ablation of permanent ice masses.

FIG. 1. 36 DISCHARGE DATA. SUNWAPTA RIVER 1977



DAILY MEAN DISCHARGE. BEAUTY CREEK FLATS

3) Rainfall runoff.

The primary control on the first two sources of runoff was the occurrence of warm, sunny weather, although the river stage remained high with high air temperatures even in cloudy weather. Rainfall was rapidly reflected in river stage and moderately high stages were noted during periods of high rainfall despite low temperatures. Rice (1979) showed (Fig 1.36b) that, for the period July 21 and August 15, 1977, mean daily discharge varied between 12.8 m^3s^{-1} and 21.2 m^3s^{-1} at the head of the Beauty Creek flats. He noted that peak discharges during this period occurred after a prolonged period of clear and hot weather, although there was a one to two day lag between a change in the weather and a noticeable change in stage. Appreciable reworking of in-channel sediments was not observed except when stage exceeded bankfull.

When discharge was derived mainly from ice and snow melt the stage typically showed a marked diurnal peak, with maximum stage occurring at approximately 6pm at the upstream end of the reach and 10pm at the downstream end. The average daily variation in stage at the distal alluvial fan under these conditions, was 20-25 cm. Rice (1979) found that the variation in stage at the upstream end of the reach was approximately 30-35 cm. He observed that a number of minor peaks were superimposed on the diurnal discharge cycle. Rice (1979) attributed these bursts of flow to variations in the rate of glacier melt. However, during the present field investigation similar fluctuations in stage were observed to result after heavy rainstorms.

1.6 The Influence of Road Construction on the Study Reach

As previously noted the eastern side of the studied reach is now confined by a road causeway (Highway 93). Initial road construction took place between 1936 and 1939, when the route was confined to the eastern margins of the valley flat. A realignment of this highway took place in 1954 with limited construction over the gravel surface. Highway 93 was reconstructed during the period 1959-1962 with major alterations to the lateral extent of the active part of the reach.

The highway runs along a causeway 2-3 m above the gravel surface. Except for limited sections the causeway lies directly upon the former alluvial surface. The major alteration to the extent of the valley train has been in the medial sub-reach where the causeway has isolated approximately 200-300 m of the flat for a length of 2 km, and has caused the main channel to shift westwards. Examination of a series of aerial photographs taken in 1959, as part of the highway survey, suggests that the highway partly follows the former dominant channel. In addition to the diversion of the main reach extensive modification was made to the pattern of Beauty Creek, which now has a single, stable channel entering the main reach through large diameter culverts under the highway. Formerly, this tributary had a braided channel pattern.

Frequent channel changes subsequent to highway construction have resulted in the impingement of flow on the highway causeway. In order to protect the causeway, a number of groynes have been built out into the reach in the vicinity of Beauty Creek. The last major period of construction was in 1971 and there has been no serious recurrence of causeway erosion since then (Frank Leong, Chief Engineer, Jasper National Park: personnal communication). In association with the groyne construction an attempt was made to divert the the main channel to the west side of the reach by dredging and gravel bank construction. This seems to have had little influence on flow routing and the remnants of the artificial gravel banks were observed to be eroding. Large volumes of alluvial gravel were excavated as borrow to facilitate highway construction. This was largely taken from inactive gravel areas, although major modifications were made to the Diadem Creek fan, with removal of part of the distal edge next to the main channel. The river appears to have readjusted rapidly after highway construction and such modifications seem not to affect the conclusions drawn from the study.

2. PREVIOUS WORK

2.1 Introduction

Examination of previous work provides a theoretical basis from which the objectives of the thesis, outlined in Chapter One, may be approached.

2.2 Downstream Variations in Grain Size

Diminution in the size of bed material of alluvial streams, with increasing distance downstream, has been widely recognised. Whilst such diminution has been implied in many studies of braided river deposits (Hein and Walker 1977, Miall 1977), statistical studies of such diminution have been relatively few (Church 1972, Bradley, Fahnestock and Rowenkamp 1972, Smith 1974, Boothroyd and Ashley 1975, Ballantyne 1978) Decreasing particle size with distance has been recognised as an important influence on the behaviour of hydraulic and channel variables (Fahnestock 1963, Nordseth 1973, Rice 1979) and also in the development of sedimentary structures and sequences (Boothroyd and Ashley 1975, Hein and Walker 1977).

The diminution of bed sediments has been attributed to two types of process, the abrasion of individual particles and progressive sorting by size. The diminution of particles due to abrasion represents wear as a result of impact, rubbing and grinding (Marshall 1927). Kuenen (1956) also suggested that abrasion occurred as a result of splitting, crushing, cracking, and chemical attack. The decline in grain size due to attrition has been described mathematically by an exponential equation of the form.

$$W = W_0 e^{-a_W x}$$ Equation 1 (Sternberg 1875)

where;

W_0 is the weight of a characteristic particle at an arbitrary starting location.

W is the characteristic weight at some distance x measured downstream.

a_W is the coefficient of weight diminution.

e is the base for natural logarithms.

Sternberg (1875) attributed this decline to the attrition of particles due to frictional forces exerted in transport (Scheidegger 1970) and indicated that the reduction in the weight of a particle was directly proportional to the work done in overcoming friction in the distance travelled (Shulits 1936).

Equation 1 may be rewritten as follows;

$$D = D_0 e^{-a_D x}$$ Equation 2

where;

D is a characteristic linear dimension of the particle at some distance x downstream.

D_0 is that dimension where x = 0.

a_D is a coefficient of size diminution

Equation 2 follows from Equation 1 as $W \propto D^3$ gives $3a_D = a_W$

Diminution due to abrasion has been simulated by tumbling mill experiments (Daubree 1879, Wentworth 1919, 1922a, Krumbein 1937). Kuenen (1956) criticised this method and designed a circular flume to demonstrate the effects of different bed conditions, water velocities and suspended sediment additions on abrasion. The experimental situation differed from natural conditions because the pebble motion was continuous, whilst in alluvial transport individual particles will be at rest for considerable periods of time. Kuenen (1955), however, noted that wet sand blasting is an ineffectual mechanism in causing the attrition of pebbles under cobble size, as the pebbles tend to be displaced by the flows causing the blasting. However, Pearce (1971) suggested that "pebble blasting" may be an effective mechanism if an individual pebble is stable as a result of imbrication.

Bradley (1970) and Schumm and Stevens (1973) noted that the experimental results, from flume and tumbling mills, underestimate observed diminution in nature. Bradley (1970) suggested that this discrepancy was the result of the use of fresh particles in the experiments and used a Kuenen-type flume to demonstrate the more rapid abrasion of weathered material. Using the arguments of Mackin (1948), he discounted differential transport as a factor causing the diminution in the size of pebbles in the Colorado River between Austin and Eagle Lake, Texas. He showed that the size diminution of granite could be completely explained by the abrasion of weathered granite. However, as Schumm and Stevens (1973) noted, there was a considerable discrepancy in the diminution coefficients between experimental and river-based coefficients, particularly for chert and quartz.

Schumm and Stevens (1973) suggested that the experimental under-estimation of diminution coefficients results because abrasion also occurs whilst particles are emplaced on a river bed. At velocities just below those required for entrainment, especially where the bed is armoured, individual particles vibrate in place. Collision between adjacent particles results in comminution without transportation. Shaw and Kellerhals (in press) combined the pebble blasting mechanism suggested by Pearce (1971) with the in-place abrasion outlined by Schumm and Stevens (1973) and proposed two components to the diminution coefficient, a_D

$$a_D = a_T + a_V \qquad \text{Equation 3}$$

where;
a_T = diminution in transport
a_V = diminution *in situ*

They concluded that approximately 90 percent of the abrasion of quartzites in the North Saskatchewan River, Alberta, is accounted for by abrasion *in situ*. This, they stated, is a function of the period of time over which abrasion *in situ* occurred, not because *in situ* abrasion is more powerful than abrasion during transport.

Mackin (1948) argued that attrition is the primary cause of the downstream diminution of grain size in "degraded" and "graded" rivers. However, he noted that in aggrading streams differential transport is an important factor causing size diminution. This contention is supported by the high values of diminution coefficients determined for aggradational features such as alluvial fans (Blissenbach 1954, Bluck 1965). Plumley (1948) suggested that between 75 percent and 85 percent of the diminution in size of pebbles in the Black Hills Terrace Gravels was caused by differential transport. Bradley *et al.* (1972) concluded that differential transport is responsible for 90 to 95 percent of the reduction in the size of gravel in the Knik River, Alaska.

Russell (1939) separated differential transport into two components: Sorting at a particular locality and progressive downstream sorting. Local sorting on the bedform scale has been demonstrated by Jopling (1964) and Brush (1965). Rana *et al.*(1973) stated that bed material transport theory predicts size sorting to result from suspended sediment transport with the median size of the suspended material varying vertically in the depth of flow and laterally across the width of the channel. They noted that bedload transport relationships are more complex, but they suggested that coarser particles are transported over shorter distances at a time. Rana *et al.*(1973) also noted that the rolling and avalanching of particles over the stoss and lee slopes of bedforms creates sorting.

Progressive sorting has been largely attributed to downstream decreases in competency (Russell 1939, Allen 1970). Russell (1939) also suggested that fluctuations in competency might result in a progressive decrease in mean grain size, with the smallest particles being moved even at minimum competency, whereas the largest particles are moved only at high competency.

Two theoretical approaches have been made in considering the initiation of motion. White (1940) considered the equilibrium of single clasts with respect to the fluid forces tending to entrain the clast and the gravitational forces resisting movement. He assumed that both sets of forces act through the centre of gravity of the clast, but the clast itself moves by pivoting around a fixed point. The analysis therefore involves the consideration of the balance of two moments, initiation of clast motion depending not only on the applied shear stress, or on the size of the clast and its submerged specific weight, but also on the angle of pivot and grain exposure.

A different approach was used by Shields (1936, in Raudkivi 1967), who related a dimensionless ratio of shear stress and gravitational forces to the boundary Reynolds number ($Re = d\,u_* / v$, where d = grain diameter, u_* = shear velocity, v = kinematic viscosity). The latter term is an expression of the grain size in relation to the thickness of the viscous sub-layer and is important in relation to drag and lift forces. The form of the relationship was verified experimentally, and the results were plotted to obtain a reasonably defined curve (Raudkivi 1967). Shields' criterion is often converted to a direct plot of grain size against average shear stress, the two being almost directly proportional for the larger grain sizes (Allen 1970, p.51, Fig 1.38).

A number of factors have been shown to cause deviation from such a relationship. Church (1972) noted that "underloose" (armoured) materials require greater shear stresses than predicted, while "overloose" sediment will experience motion at lower values of critical shear stress than predicted. Similarly, where grains rest on a sloping surface, lower values of shear stress will be required to initiate motion than predicted by Shields' relationship. Shear stresses themselves deviate widely fom average values. Instantaneous values of shear stress may reach up to four times the average values.

Ashmore (1979) noted that large grains may be entrained more readily than small ones and he suggested that this might be due to the larger grains possessing a lower angle of pivot than smaller ones. Chang (1939), however, earlier suggested that such preferential entrainment may be the result of the larger grains projecting higher into the flow and being exposed to greater velocities. The preferential entrainment of larger grains was observed by Straub (1935) in flume experiments, in which a size gradation from fine to coarse developed downstream. Everts (1973) noted a tendency for larger grains to move more easily over a fine bed than grains of the same size as the bed and Church and Gilbert (1975) reported several cases where coarse grains were entrained preferentially. Furthermore, as Ashmore (1979) noted, even where there is a large size range present, there is very little difference in the critical tractive force for a large proportion of the bed material, so there is a tendency for a considerable portion of the load to move at the same time. In the light of the above evidence it is unlikely that relationships between tractive force and grain size can account solely for sediment sorting patterns.

Bradley (1970) suggested that gravel transport occurred intermittently and that when in transport smaller particles move faster and more frequently than larger particles, with a resulting separation in sizes. Meland and Norrman (1969), however, showed that for natural material between 0.85 and 7.0 mm in diameter, maximum transport velocities occurred in the coarser fractions. They suggested that the faster moving, coarse, fractions are deposited earlier and collect at the base of the accretion mass. Hence, in an aggrading situation progressive fining may occur with the finer, slower-moving fractions being deposited over the faster-moving fractions.

However, Laronne and Carson (1976) in field experiments, and Koster (1977), found that maximum transport velocities occurred when clasts were of intermediate size. Koster (1977) noted that this "optimum" size of transport was dependent on a ratio between nominal diameter and flow depth (dn/Y). He found that maximum velocities for large pebbles occurred when values of this ratio were between 0.3 and 0.6. Below this range transport velocities were slower and dependent on clast size, but above this range, as the values of the ratio approached unity, transport velocities were dependent on the competence of the flow. Hence it may be suggested that the mechanism proposed by Meland and Norrman (1969) does not completely explain size sorting at an aggrading location. This may result from a more rapid burial of intermediate sized clasts and a lower frequency of large clast transport.

Rana *et al.*(1973) attempted to provide a theoretical basis for the downstream diminution of grain size in alluvial channels caused by differential transport. They introduced a number of assumptions.

1) Flow in the channel is steady and constant. The channel section, and hence discharge intensity of flow, remain constant downstream.

2) The channel profile is an independent variable.

3) The channel slope decreases exponentially in a downstream direction in the form,

$$S = S_0 e^{-\gamma x}$$

Equation 4.

where;

S = local channel slope.
x = distance from an upstream reference section.
γ = coefficient of slope reduction.

4) The channel is in equilibrium, but it initially formed as a result of the aggradation of material transported from upstream.

Using Einstein's (1950) bedload formula, for a given discharge intensity of flow and bed material load concentration (and the above assumptions), they showed that the median bed material size decreased exponentially downstream.

$$D_x = D_0 \, e^{-a_D x}$$

Equation 5.

where;

D_x = the median diameter of the bed material at the beginning of the reach.

D_0 = the median diameter of the bed material at the end of the reach.

a_D = coefficient of bed material size reduction.

x = distance.

They concluded that;

1) If the energy gradient decreases exponentially, the bed material size also decreases exponentially.

2) The coefficient of bed material size reduction along the reach was not constant over long reaches, but decreased if the flow regime, defined by Froude number, changed from upper to lower.

3) For two channels with different energy gradients and different flow characteristics, but the same bed material transport, the coefficients of bed material size reduction should be the similar.

A comparable analysis was undertaken by Deigaard and Fredsoe (1978). Unlike Rana *et al.* (1973), they introduced no assumption that the bed was initially in equilibrium. They showed theoretically that as a bed aggrades, the grain size at a given downstream location initially decreases, but eventually reaches a constant size. The length of time taken for this equilibrium to be reached is dependent on the distance downstream. Their analysis, like that of Rana *et al.* (1973), showed that mean grain size decreases as the slope of the river declines, and for a given longitudinal profile, the downstream diminution in grain size is uniquely determined by the sediment input and water discharge.

Whilst the adoption of an exponential form for the energy gradient in alluvial rivers may be valid in a short term analysis, other workers have suggested alternative slope–bed material size relationships. Plumley (1948) concluded that the bed material size reduction only showed an exponential form if the slope showed a similar exponential form. He further concluded that grain size decline was also dependent on discharge, streams with greater discharge having a faster rate of decline. However, his analysis is complicated by the use of $\log_2$ rather than $\log_e$ in the calculation of the diminution coefficients. Scheidegger (1970) reported that Lokhtin (1897) outlined a causal relationship between the slope of the river bed and the size of bed material. For a given river a balance on the bed was considered to exist in the following form.

$$C_f = D/S$$ Equation 6.

where;
C_f is a constant coefficient of fixation.
D is a characteristic linear dimension of the bed material
S is the slope.

However, other workers, (Shulits 1941, Macklin 1948, Tanner 1971) have argued that slope is a function of grain size. Shulits (1936) indicated that in many rivers slope is proportional to particle weight and using Sternberg's (1875) relationship he obtained;

$$S = S_0 e^{-a_w x}$$ Equation 7.

where;
a_w = coefficient of weight reduction.
S = Slope.

The correspondence between this equation and the actual river profiles has been noted (Krumbein 1937, Tanner 1971). A number of studies have shown a high correlation between particle size and slope (Hack 1957, Miller 1958, Brush 1961). However, as Brush (1961) suggested, the causes of particle size – slope relationships are largely unresolved.

2.3 Causes of Variability Around Downstream Relationships

In previous studies considerable variance has been noted around relationships describing downstream changes in grain size (Miller 1958, Church and Kellerhals 1978, Knighton 1980, 1982) In part, this variation may be explained by local site influences such as differences between riffle and pool sediments (Scott and Gravelee 1964, Church 1972). However, even where attempts were made to minimise local site influences, considerable variation remained (Church and Kellerhals 1978).

A major disturbing influence on downstream trends in grain size is the input of fresh debris from bedrock and bank erosion (Miller 1958, Brush 1961, Knighton 1980). However, tributaries may have a similar influence. The effect of a tributary input on the general trend in grain size will largely depend on the amount and composition of the input relative to the main stream (Knighton 1980). Church and Kellerhals (1978) noted that, barring physical interaction (i.e. direct attrition) between the input and the main stream sediments, two distinct populations should occur in the sediments downstream of a confluence. However, given that such populations may not be recognisable from limited sampling they suggested that, under certain conditions, mean grain size might increase. The persistence of the effect of the tributary input largely depends on the rate of dispersal of the input away from the confluence (Todorovic 1975). For the braided Knik River, Alaska, Bradley *et al.* (1972) found that the mixing of tributary inputs was limited, with the contributed sediment remaining on the same side of the reach for up to 8 km.

In braided rivers and outwash considerable surface variabilty has been noted. Church (1972) recognised that trends in channel sediments were more irregular than those on the sandur surface itself. Ballantyne (1978) described sediment trends over a small sandur on Ellesmere Island. He determined three flow stages, and noted that on the lower main flow area both channel sediments and bar surface sediments diminished in size downstream. The bar sediments were generally finer than the channel sediments, although the trends converged with distance. Similar, but less well defined, trends were identified on the floodplain and terrace surfaces.

2.4 Variations in Particle Shape

Variations in particle shape have been considered in terms of roundness (Krumbein 1941, Sneed and Folk 1958, Church 1972, Knighton 1982, and others), sphericity (Krumbein 1942a, Sneed and Folk 1958, Helley 1969, and others) and by the use of axial ratios (Sneed and Folk 1958, Bradley *et al.* 1972, Church 1972).

2.4.1 Particle Roundness

Roundness measures describe the surface morphology of a particle, usually in terms of a ratio between a measure of curvature of the particle outline and a linear dimension of the particle (Wentworth 1922a, Wadell 1932, Kuenen 1956, Cailleux 1947). An alternative method was proposed by Krumbein (1941) who produced a visual comparison chart based on the measure devised by Wadell (1932).

The development of roundness for rock particles was investigated in tumbler and flume experiments by Daubree (1879), Wentworth (1919, 1922a), Krumbein (1941) and

Kuenen (1956). They noted that the rate of roundness increase with distance was initially rapid, but then showed a marked decline, (at approximately 5-7 km: Krumbein 1941) eventually approaching an asymptotic value. The initial high rate of roundness increase was attributed by Wentworth (1922a) and Krumbein (1942b) to the removal af sharp corners by chipping. Krumbein (1942b) argued that roundness was subsequently controlled by sphericity; increasing sphericity leading to increased roundness. Plumley (1948) disputed Krumbein's (1942b) analysis and stated that the change in roundness with distance was directly proportional to some power of the distance and to the difference between the roundness of a particular clast at a certain distance and a limiting value of roundness. Wentworth (1922b) and Kuenen (1956) both found a relationship between the rate of roundness increase and particle size. The latter author found larger pebbles became more rounded than smaller pebbles with transport over the same distance.

Similar behaviour also seems to occur under field conditions. Wentworth (1922b), Plumley (1948), Blissenbach (1954) , Sneed and Folk (1958), Pearce (1971) , McPherson (1971) , Church (1972) and others, found an increase in roundness with distance. In many cases, as in the flume experiments, roundness increase with distance was initially rapid, with a subsequent decline in the rate (Wentworth 1922b, Plumley 1948). Kuenen (1956) suggested that this initial rapid increase was a result of higher velocities in upstream reaches, pebbly stream beds, larger particle sizes, and chipping. He attributed the later decline in the rate of rounding to lower downstream velocities, sandier stream beds, smaller particle sizes and a reduction in the effectiveness of the chipping process. However, Russell (1939) and Pittman and Ovenshine (1968) noted that, under conditions of high velocity, roundness may temporarily decrease due to clast breakage. Krumbein (1942b) argued that observed downstream changes in roundness may be partly a result of differential transport, smaller rounder particles being transported more easily. This idea was supported by Pashinskiy (1964) who noted that less angular particles are more easily entrained.

2.4.2 Particle Form

Particle form is most commonly investigated using a sphericity measure. In tumbler experiments Krumbein (1942b) found that after a small initial increase there was little change in sphericity. This finding has been supported by many field studies, several authors finding no systematic relationship between sphericity and downstream distance (Plumley 1948, Blissenbach 1954, Miller 1958, Brush 1961, Bluck 1965, and Church 1972). However, Unrug (1957) found that sphericity decreased downstream in the Dunajec Valley. He attributed this to shape sorting whereby pebbles with low sphericity were transported more easily.

Sneed and Folk (1958) found that sphericity showed a complex relationship with particle size, lithology and distance of transport. For pebbles between 30 and 70 mm in diameter, they found that quartz had the highest sphericity and this increased with transport. Chert had an intermediate sphericity but this decreased with distance due to breakage. Limestone had low sphericity and, due to breakage along bedding planes, showed no consistent changes in sphericity. Pebble size had no consistent effect on the sphericity of limestone, but larger chert and quartz pebbles (54–70 mm) had a lower sphericity than smaller ones (30–38 mm). This effect became more pronounced with downstream distance. They suggested that pebbles larger than a certain size (39mm for chert, 64mm for quartz) would show a downstream decrease in sphericity and pebbles smaller than this size would show an increase in sphericity downstream. They concluded that the absence of significant distance – sphericity relationships in other field studies was due to the failure of other workers to assess size – sphericity relationships.

A number of workers have suggested that particle form influences transport velocities and ease of entrainment, with a resultant sorting with distance according to form. Krumbein (1942a) found that transport velocity was directly related to rolling velocity and noted that elongated particles tended to roll faster. The contention that rolling, and hence transport, velocities of spherical particles are greater was supported by Russell (1939) and Plumley (1948). Helley (1969) found that, of all particle shapes, spherical particles were most easily entrained. However, for conditions of suspension transport various workers have suggested that particles with high sphericity settle faster and, therefore, are transported less rapidly (Wadell 1932, Krumbein 1942a, Lane and

Carlson 1954) . Meland and Norrman (1969), however, reported poorly defined relationships between shape and transport velocity. Lane and Carlson (1954) suggested that, for a given weight, platey particles are less easily transported than spherical particles, possibly due to imbrication, but that for similar diameter, platy particles have a lower weight and are, therefore, transported more easily. Koster (1977) found that the degree of oblateness (disc) and prolateness (roller) exerts a strong control over transport velocities, and concluded that where there was a low clast size to depth ratio, oblate forms are transported more readily because of their susceptibility to hydraulic lift into faster moving levels of the flow. For larger clasts, and hence higher values of the clast size - depth ratio, he found that prolate forms are more readily transported, because of the high shear exerted in the lower levels of the flow profile.

Under field conditions, both Unrug (1957) and Bradley *et al.* (1972) found that the least mobile particle shapes were spheres and rods, and that blades and discs were preferentially transported. Bluck (1964) found, in aggrading locations on a southern Nevada alluvial fan, a downstream increase in rods and discs. He suggested that the preferential transport of rods occurred under bedload transport and of discs in suspension transport. Church (1972) found no significant changes in the proportions of the various Zingg (1935) classes downstream although he noted that the number of spheroids and blades increased slightly at the expense of the numbers of discs and rollers.

Field and experimental studies, in general, have shown that strongly oblate or prolate clast shapes are preferentially transported (Unrug 1957, Bluck 1965, Bradley *et al.* 1972, Koster 1977). This is at variance with the findings of Krumbein (1942a) and Helley (1969) who found that spherical particles are more readily transported. Lane and Carlson (1954) supported the contention that oblate particles are more easily transported, but suggested that this was merely due to their lower weight, for a given size, as compared to spherical particles.

2.5 Sediment Size Variations over Bars

Comparison of the literature on sediment variations over exposed depositional areas is complicated by the plethora of terms given to such fluvial forms (Smith N.D. 1978). A further problem is that the features may be site specific, as each field location tends to possess unique environmental parameters, for example reach slope and grain size.

Within this study it is hoped not to add to to terminological problems. Allen (1968 p 40) defined a bar, "as a bedform which may or may not be exposed at a particular stage, and which has the dimensions of the same order as the channel in which it occurs." In a braided river environment a distinction may be made between "unit-bars" (Smith N.D 1974) and "braid bars" (Allen 1968). Smith (1974 p210) defined unit-bars as "relatively unmodified bars whose morphologies are determined by mainly depositional processes." Bluck (1979) argued that these bars are the basic units of sedimentation from which braid bars develop. It may be suggested that the majority of the features described in the literature are of this latter form. Within this study it is proposed to adopt Bluck's (1979) classification for braid bars

1) Medial bars; a bar form surrounded by active channels.

2) Lateral bars; a bar form attached to an existing bank area.

Smith N.D. (1974) and Bluck (1979) argued that braid bar development results from the coalescence and modification of unit bar forms. This developmental sequence was also identified by the studies undertaken by Hein (1974) and later outlined in Hein and Walker (1977). However, other workers have suggested that braid bars result from the development and emergence of single unit bars (Krigstrom 1962, Rust 1972, Gustavson 1974).

Smith N.D.(1974) suggested that unit bars are initiated when gravel is deposited as a result of a local hydraulic change reducing sediment transport capacity. Hein and Walker (1977) similarly argued that most unit bars develop initially from a lag which is emplaced at maximum flow stage as a diffuse sheet. Observations by Krigstrom (1962), Smith N.D. (1974) and Bluck (1979) indicated that these sheets develop in areas of diverging flow, frequently downstream of erosional scour pools. Ashmore (1979) identified three basic situations in which bar development may occur;

1) Downstream of scour holes involving the junction of two or more channels, in channel bends, or where flow is confined by a bar upstream.

2) Downstream of flow expansion either where a steep confined channel segment emerges into a less confined reach, or where a dominant channel aggrades sediment into a scour hole.

3) Where flow overtops a bank. The reduction in depth and flow velocity produces deposition in the form of a shallow sheet or lobe.

Leopold and Wolman (1957), Krigstrom (1962) and Hein and Walker (1977) suggested that an initially emplaced gravel lag forms into an emergent bar by vertical aggradation. Leopold and Wolman (1957) and Krigstrom (1962) also indicated that downstream additions to the emerging bar also occurred and the combined effect of vertical and downstream accretion progressively forced more water into the lateral channels. Leopold and Wolman (1957) suggested that these channels may both deepen and widen, with bar emergence occurring as a result of downcutting. Krigstrom (1962) noted that flow diverges over bar surfaces which form transportation surfaces. The lower slope of the bar surfaces relative to the water surface slopes in the adjacent channels causes the downstream margins to emerge first. Similar conclusions were reached by Gustavson (1974) working on a braided reach with fine gravel sediments. He noted from fabric orientation that flow diverged over the surfaces of both longitudinal and point bars. He further suggested that the downstream margins of longitudinal bars grew with accretion on avalanche slip faces orientated transversely to the flow. He indicated that bars tended to be overlapping lobes rather than discrete sheets of sediment.

Ashmore (1979) identified three processes by which unit bar modification occurs;

1) The incision of a single channel into the bar surface. A narrow trough is cut into the centre of the bar surface. The trough gradually widens, deepens and captures most of the flow and results in abandonment of the flanks of the original bar.

2) Lateral migration and avulsion. Where bars are asymmetrical to the flow, and aggrading into a scour pool (the diagonal bars of Smith N.D. 1974) , the deflection of the main current by the bar leads to scour against the opposite bank. The downstream extremity of the bar tends to have the shallowest flow and as the channel

widens this area is abandoned. At low flow these bars are modified by dissection of the avalanche face. Immediately downstream of the bar the secondary currents in the scour pool move material back towards the inside of the bend. This is deposited as either another asymmetrical bar or in the form of gently dipping sheets with stepped fronts facing the inside of the bend.

3) Channel division. The shallowest portions of a bar, if the bar becomes inactive, form a nucleus around which flow splits. This often results in the destruction of the avalanche face and the development of new bar lobes, usually with foresets orientated obliquely to the channel and facing away from the nucleus.

Hein and Walker (1977) suggested that the rate of aggradation controlled the downstream morphology and resultant internal structure of unit bars. Krigstrom (1962) pointed out that the form of existing channels was a dominant control on bar form. Smith N.D. (1974) recognised four types of unit bars.

1) Longitudinal. These are approximately diamond shaped and elongated parallel to the flow.

2) Transverse. These have straight, lobate or sinuous margins and broad surfaces that are either flat or have axial depressions. The margins are either steep foresets or riffles of low slope.

3) Point bars. These form in gently curving channels, and are commonly separated from the inner convex bank by a smaller channel and have low surface slopes dipping towards the outer convex bank.

4) Diagonal bars. These are orientated obliquely to the flow and show a triangular cross-section with the down-current margins consisting of riffles or avalanche faces.

Hein and Walker (1977) recognised similar morphological features, but suggested that such bars should be classified in terms of whether they had well defined, downstream, foreset margins. If water and sediment discharges are high the initial diffuse sheet lengthens downstream faster than it aggrades and no foresets develop. This form is typical of longitudinal or diagonal bars. Under lower flow, sediment discharge is lower, and vertical accretion with a foreset margin takes place.

Smith N.D. (1974), later supported by Bluck (1976, 1979), observed that unit bars were the basic element of size segregation and tended to show the following trends.

1) The upstream portions of active unit bars were composed of sediment similar in size to adjacent channels.

2) Bar sediments fined downstream.

3) Bar sediments showed a general fining-upwards trend.

Smith N.D.(1974) argued that unit bars which evolve over several discharge periods may show grain-size distributions varying from the simple model above and that where severe modification by erosion, or new depositional patterns occurred, grain-size trends would be highly variable. He stated that under such circumstances complex "braid bars" develop.

Ore (1964) suggested that individual unit bars form the nuclei for large scale longitudinal bars, additions of sediment occurring at the downstream ends in wedge form. Bluck (1979) outlined a sequence by which individual unit bars evolve into braid bars. He stated that if a unit bar resists movement within the channel, then by the addition of sediments it may grow into a medial bar. If the bar continues to move downstream, he suggested, it may dissipate over the next riffle-pool complex, or may become attached to one bank and become a lateral bar. Bluck (1979) indicated that further individual bars may become attached to either of these bar forms in the creation of a "mosaic" bar. However, he also suggested that lateral bars may grow by the continual addition of unit bars which amalgamate to form a larger unit with a uniform grain size decline from the channel margin to the inner bank.

Ashmore (1979) outlined three examples of sequences of events which may lead to braid bar formation;

1) Where deposition occurs around a small exposed nucleus as a result of the migration of two channel of asymmetric cross section. (The channels initially diverge around the nucleus and rejoin downstream in an elongated scour trough.) Ashmore (1979) identified several related features;

a) A partially infilled central trough often showing waning-flow scours.

b) Evidence of a slight upstream migration of the channel bifurcation, producing a secondary nucleus and a coarse veneer upstream of the original one.

c) Convergent elements consisting of former channels infilled by sheet deposits.

d) Overlapping sheets produced by lateral migration, particularly in the downstream portion of the bar.

e) Bar lobes formed by the present active channels. He stated that the upstream half of such complexes tend to show remnant bar lobes, while the downstream portion is apparently dominated by overlapping sheets. Migration of this kind, involving only one channel, would produce a lateral bar of similar construction.

2) Where lateral migration of a channel containing an asymmetric or diagonal bar occurs, deposition adjacent to the bar nucleus may produce an area consisting of sheets and lobes.

3) If a channel containing a bar is abandoned, due to upstream diversion or avulsion, a complex bar may result from deposition in the former channel.

Rust (1972), however, proposed an alternative hypothesis of bar formation, at variance with other work. He stated that in the Donjek River, Yukon, bars were essentially immobile except under peak flow. He inferred, from a predominance of horizontal bedding, that gravel transportation occurs in planar sheets under high energy flow and suggested that the primary area of deposition is the flatter upstream area of the bar surface and hence bars migrated upstream.

2.5.1 Structural and Directional Properties

Braid bars, both of medial and lateral form, tend to show a preferred orientation parallel to the local flow direction (Ore 1964, Rust 1972). Both Rust (1972) and Gustavson (1974) suggested that medial bars have a plan shape similar to a rhomboid or pointed ellipsoid. Rust (1972) noted that such bars were asymmetric both parallel and normal to the flow. Parallel to the flow this asymmetry took the form of a gently sloping upstream surface which graded into the shallower water above the bar, and a steeper downstream slope which merged laterally into the steeper bank of the adjacent channel.

Normal to the flow, this asymmetry took the form of a ridge parallel to the bar axis, usually nearer to one side. Krigstrom (1962) , Rust (1972) and Boothroyd and Ashley (1975) noted the existence of erosional margins to bars, principally on the downstream portions. Fabric and sedimentary structure orientation have been shown to be similar to local channel directions (Rust 1972, Gustavson 1974) . However, both Gustavson (1974) and Bluck (1979) indicated that estimated flow directions diverge over the bar surfaces.

The surfaces of braid bars are widely recognised to be complicated by minor channels (Krigstrom 1962, Ore 1964, Williams and Rust 1969, Rust 1972, Bluck 1974, 1979, Gustavson 1974, and Boothroyd and Ashley 1975). Ore (1964) , Williams and Rust (1969), and Gustavson (1974) argued that these are a post-depositional modifications of the bar surfaces. Krigstrom (1962) and Bluck (1979) suggested that these modifications occur during the emergence of the bar surfaces. Williams and Rust (1969) noted that such dissection produced small "terraces" parallel or sub-parallel to the channel margin with a vertical interval of less than 30 cm. They suggested that the channels may be discordant, or erosional, relative to each other. Their extent may be limited, the channels variously grading out, either upstream or downstream, or coalescing.

A number of minor structural features have also been recognised on bar surfaces.

1) Scour pits, ellipsoidal scours, and scour holes.

Gustavson (1974) recognised scour pits on bar surfaces. These are broadly U-shaped, erosional depressions which open downstream. Downstream of each pit is an elevated area of limited extent. Pits range in size from 0.5 m to 3 m across at the base. They occur either singularly or in irregular groups. These features may be possibly equated with the scour hollows described by Williams and Rust (1969) which are of short lateral extent and elliptical in outline. They tend to be deeper than 30 cm and erosion extends through several strata. Williams and Rust (1969) also recognised smaller scale features, ellipsoidal scours, which are elliptical in outline and are elongated parallel to the flow. The depressions become shallower downstream. Upstream from a depression is a small sub-horizontal bar.

2) Deltas, chute bars and sand wedges.

Bluck (1979) recognised two waning-flow, sand features.

a) Chute bars which occur at the downstream end of semi-permanent channels in the bar head, and are also present in lateral minor channels.

b) Deltas which build out laterally into minor ("inner") channels from the bar surface. These may be similar to the sand wedges recognised by Rust (1972).

3) Transverse ribs and stone cells.

These were recognised by McDonald and Banerjee (1971), Gustavson (1974) and Bluck (1979) and may be described as cobble or boulder ridges orientated transversely to the flow. The ribs are generally one to two clasts high and several clasts wide. The inter-rib areas generally have finer grain sizes than the ribs themselves. Pebbles and cobbles on the ridges are orientated transversely to the flow and tend to be imbricated, dipping upstream. Gustavson (1974) and McDonald and Banerjee (1971) found that transverse ribs tend to be located in the central portions of riffle sections of channels. McDonald and Banerjee (1971) suggested that the ribs constitute an equilibrium bedform in the higher gradient riffle sections of gravelly alluvium. The antidune origin of transverse ribs has been partially confirmed by flume investigation (Shaw and Kellerhals 1977, Koster 1978). Bluck (1979), however, found transverse ribs covering imbricate discs on bar surfaces. The orientation of the ribs varied from the underlying gravel and thus he suggested that ribs are generated at lower flow stages than those causing bar emplacement.

4) Lineated gravel.

Rust (1972) and Bluck (1979) recognised lineated gravel on bar surfaces. Rust (1972) described this as comprising irregular, low, ridges orientated parallel to the flow. He suggested that the ridges result from secondary transverse flow in tube-like vortices orientated parallel to the main flow direction. Bluck (1979) argued that the lineations were produced at high stages in the lee of protruding clasts and were modified at lower stages of flow.

5) Beach ridges, levées and spits.

Rust (1972) recognised sand accumulations formed at the margins of bars in areas protected from the main current. The ridges form at the breaking point of waves generated by the primary current flow. Similar features, which he termed levées, were recognised by Ashmore (1979) in a flume experiment. These levées formed by washover along channel margins. If present in natural gravel streams, levées should occur in fine gravel. Bluck (1979) recognised spits which he described as water-marginal features built across the mouths of abandoned channels.

6) Ripples and current crescents.

Ripples have been recognised in sand on bar surfaces by many workers (Williams and Rust 1969, McDonald and Banerjee 1971, Gustavson 1974, Bluck 1979). Williams and Rust (1969) noted that they are preserved mainly in abandoned channels. Frequently these ripples are covered with silt drapes (Williams and Rust 1969, Gustavson 1974). Current crescents have been recognised by Williams and Rust (1969) and McDonald and Banerjee (1971). They occur where isolated pebbles rest on sand, and comprise a crescentic hollow eroded around a pebble, deepest at the upstream end. A longitudinal ridge of material, diminishing in height downstream, occurs to the lee of the pebble.

2.5.2 Sediment Size Patterns over Braid bar Surfaces

Sediment size patterns over braid-bar surfaces have received little attention. As previously noted Smith N.D. (1974) suggested that sediments of unit bars tend to fine downstream. However, he also noted that where they coalesce in modified braid bars grain size patterns are expected to be highly complex. This contention was supported by Bluck (1976) who noted many areas exhibiting rapid lateral changes in grain size.

Ore (1964) suggested that coarse sediment was concentrated at the upstream end of medial bars, and fine sediment at the downstream end, with a sharp line of demarcation separating the two zones. A similar decline was noted by Boothroyd and Ashley (1975), who found that the coarsest material was concentrated on the upstream apex, with a large decrease in grain size down the bar, parallel to the flow direction. They noted that sandy slip-faces occurred in the distal areas of the bars, and that the areal extent of sand on bar surfaces increased as the gravel grain size decreased downstream.

Bluck (1976, 1979) recognised a distinction between a coarse bar "platform" and the more extensively exposed bar "supra-platform" overlying it. He distinguished between sediment size patterns on coarse grained, intermediate grained, and sand braid bars. In coarse grained sediments (largest grain size > 100mm), he recognised a coarse bar head of imbricate clasts, fining downstream. As previously noted, these imbricate clasts were overlain by transverse ribs which Bluck (1979) suggested developed at a lower flow stage. Bluck (1979) further found fine gravel sheets, infilling spaces between large clasts located at the margins of the bars. He suggested that these were also emplaced at low flow stage conditions. He also noted that the bar tail area was topographically lower than the head, and stated that the sedimentary patterns may record exclusively lower flow deposition. The coarsest material recorded by Bluck on the bar tail was located on the bar lee face. Sand sheets were found to overlie the bar lee face and formed lateral infills of minor channels.

For intermediate grained deposits (25-40 percent gravel, maximum grain size 20-60 mm), Bluck (1979) found that, in comparison to bars in coarser material, the bar head deposits differed only in that transverse ribs were absent. However, the bar tails were found to be more extensive with sand sheets occupying up to 80 percent of the bar surface and sometimes merging into complex bar lee areas. Bluck (1979) further described a veneer of gravel overlying sand, which he suggested was not a lag deposit, but was emplaced on the sand surface during low flow stage.

3. METHODS

3.1 Investigation

Fieldwork was undertaken, on the Beauty Creek flats, between June 2nd and August 25th, 1981. The objective was to obtain data representative of variations in the surficial sediments over the reach in order to analyse the following;

1) a) Downstream variations in grain size and sorting.
   b) Downstream variations in particle shape
   c) The influence of tributary inputs on the above
2) Sediment size variations over small areas.

3.2 Sampling

A total of 103 gravel samples and 10 sand samples were taken from the Beauty Creek flats, and a supplementary gravel sample was obtained from the active margin of the Diadem Creek alluvial fan. The sampling was stratified, 57 cross-reach transects being delimited at 200 metre intervals. In each sub-reach the first transect was located relative to a known landmark (e.g. the apex of the Wooley Creek alluvial fan), subsequent transects being located by paced distances from this point. In order to control errors introduced by this method the transects were periodically relocated with reference to other known landmarks. A number of deviations from this spacing must be noted.

a) Proximal sub-reach

The first four transects were spaced at 150 metre intervals. This spacing was controlled by the availability of suitable sampling sites, and a desire to sample the area with a closer spacing due to the apparently rapid diminution of grain size in the proximal zone.

b) Distal sub-reach

i) The initial five transects were spaced at irregular intervals. This was due to these samples being taken individually and located by, compass triangulation, with reference to known landmarks (e.g the Beauty Creek culvert), within a general grid sampling scheme.

ii) Subsequent transects in the distal reach, were spaced at 190 m due to a consistent measurement error, which resulted from underestimation of the length of an individual pace.

A discontinuity occurs in the spacing between the first and last transects of adjacent reaches, as a separate origin was assigned to each sub-reach. For instance, the spacing between the last sample in the proximal sub-reach and the first sample in the medial reach is approximately 70 m. Whilst the method by which the transects were located resulted in an error in spacing in the lower reach, the transects within reaches are spaced regularly and the measurement error is known. The cumulative error of placement of the last sample has a maximum of 50 m, and is only 20 m at the last sample in the middle reach.

For each transect a sample was taken adjacent to the main channel, and where more than one channel occurred on the active gravel area at least one sample was taken adjacent to a minor channel. Downstream of the major tributaries (Wooley Creek, Beauty Creek), three samples per transect were taken for six transects to examine lateral variations of sediment properties in the reach. As most samples were taken at relatively low flow stages there were few access problems and the samples were widely distributed over the active gravel areas.

Individual samples were located on geomorphological criteria, with samples being taken, preferentialy, at the head of the exposed bar nearest to the delimited transect. Church and Kellerhals (1978) used a similar procedure. Where such sample sites were not available, samples were taken from a channel margin. Whilst the hydraulic conditions causing deposition at bar head and channel margin locations are unlikely to be the same, it was felt that consistency was maintained during the sampling by selecting the coarsest gravel from within a general area. At each sample site 100 clasts were taken using a stratified sampling scheme. Five, two metre transects were placed randomly over the sample area using a metric tape. Clasts were then selected beneath each 10 centimetre marking. Where a clast was located under more than one 10 cm marking it was not remeasured, although sampling for clast size, in theory, requires this. The measurement of separate clasts is required to obtain a representative value for mean clast roundness.

Where possible the sand samples were obtained from bar head locations. A small quantity of sand, approximately 300-400 grams, was scooped from the upper five cm. In a few cases there was no sand exposed in the vicinity of the delimited transect and in such cases a grab sample was obtained from the bed of the river at low stage.

3.3 Field Mapping

Sediment size patterns over depositional areas were characterised by maps of three representative locations, selected from the proximal, medial and distal reaches. The map locations were chosen on the following grounds;

1) Size. The areas mapped represent medium sized gravel bars, with an axial length of 90-160 m, which could be mapped over a few days.

2) Morphology. Each area chosen had well defined channel margins. The areas were wholly exposed at low stage.

A 10 metre square grid was established over each area as a basis for mapping. A similar grid was drawn on the mapping sheet at a scale of 1:200 and features to be depicted were sketched relative to this grid. Morphological features such as channel margins, minor banks and scours were mapped and the margins of gravel sheets were delimited. During the mapping process a visual categorization of the various sediment grades was made according to the following scheme. The size classes represent a later approximation (see Fig 3.1)

Sand (less than - 1.0 phi)
Very fine gravel (-3.4 to -3.8 phi)
Fine gravel (-3.8 to -4.3 phi)
Fine-medium gravel (-4.3 to -4.7 phi)
Medium gravel (-4.7 to - 5.02 phi)
Medium-coarse gravel (-5.02 to -5.5 phi)
Coarse gravel (-5.5 to -6.0 phi)
Very coarse gravel (greater than -6.0 phi)

Gravel samples were also taken from the major gravel sheets. The samples collected comprised 50 clasts selected at 10 centimetre intervals on a five metre transect located wholly within a delimited gravel sheet. The B-axis of each clast was measured using a ruler. The number of samples taken at each sub-reach were;

Proximal sub-reach	22
Medial sub-reach	40
Distal sub-reach	24

3.4 Sample Analysis

3.4.1 Sample Measurement

Initial analysis of the gravel samples was undertaken in the field. The majority of the samples were bagged and measured at a later date, although some of the coarser samples were measured *in situ*. The long, intermediate and short axes of each clast were measured, these being mutually orthogonal. However, following Flemming (1965) they were not required to intersect. The majority of the samples were measured using calipers, to an accuracy of one millimetre. A limited number of samples were measured using a millimetre scale. These were largely confined to a few large clasts in the coarser samples, and to the finer samples where the manipulation of the calipers was difficult. The samples were measured by a number of operators although no attempt was made to assess differences between operators, as the measurements were carried out predominantly by the author.

The sand samples were analysed for grain size by sieving 200 grams of each sample mechanically, for twenty minutes, through sieves spaced at half phi intervals from −4.0 phi to +4.0 phi. Additional sieves were added at 1.75 phi, 2.25 phi and 2.75 phi because of the large amounts of sand retained on the 2.0 phi, 2.5 phi and 3.0 phi sieves. Grain size distribution curves of cumulative percentage weight finer than a certain size were plotted against phi grain size on probability graph paper. A mean grain size (M) was obtained using the MacCammon (1962) measure:

$$M = \frac{\phi 5 + \phi 15 + \phi 25 + \phi 35 + \phi 45 + \phi 55 + \phi 65 + \phi 75 + \phi 85 + \phi 95}{10}$$

which Folk (1966) showed had an efficiency of 97 percent as compared to a moment measure. In order to obtain a quantitative estimate of the roundness of an individual clast, the minimum radius of curvature on the principal plane was assessed by visual comparison against a nomogram comprising a number of curves of known radii. This method, suggested by Cailleux (1947) was used by Church (1970). The Cailleux roundness measure involved the calculation of a ratio using the longest dimension of the clast.

$$R = 2r / A$$

where;

r = minimum radius of curvature on the principal plane.
A = a axis length.

An alternative method of assessing roundness, as suggested by Krumbein (1941), is to estimate roundness by visual comparison against charts depicting clasts of different roundness. However, as Griffiths (1967) noted, operator variance causes visual techniques to be of low efficiency in terms of the replication of results.

Individual clasts were classified in six broad lithologic categories;

1) Quartzite. Demonstrating a variety of hues from yellow-brown to white to pinkish-red

2) Sandstone. Relatively low in frequency of occurrence this demonstrated a variety of forms, from well cemented, quartzitic sandstone to poorly cemented, fine grained sandstone.

3) Limestone. Predominantly fine grained and grey or black in colour. As noted from the geological descriptions of the locale, a number of limestone units are present in the area. No attempt was made to differentiate clasts from different beds.

4) Limestone/dolomite. Limestone with substantial (>30% by surface area) dolomite inclusions, or predominantly dolomite. The dolomite was grey to creamy white in colour, and occasionally showed calcite inclusions.

5) Conglomerate. Pinkish-red occasionally green in colour. Well cemented with a grain size ranging from coarse sand to small pebbles.

6) Other, including calcite and shale. These had a very low frequency of occurrence.

3.4.2 Data Analysis

Subsequent analysis of the gravel sample data was accomplished by the use of a computer program originally written by Church (1970) to analyse similar gravel samples from sandurs on Baffin Island. The original program printed or calculated the following items from an input file containing, the three axis measurements, the minimum radius of curvature on the principal plane, and a lithology code.

a) i)The Cailleux roundness index (R) for each clast

ii) An inverse of the Cailleux flatness index (F) clast.

$$F = 2C/A+B$$

where;

A = length of longest axis
B = length of intermediate axis
C = length of shortest axis

iii) Intercept sphericity (S) for each clast.

$$S = (BC/A)^{0.333}$$

b) The first through fourth moments of the distributions of A-axis, B-axis, C-axis, roundness, flatness, sphericity.

c) A tabulation of the sample distribution of the intermediate axis by whole phi classes.

d) A tabulation of the distribution of the parameters of roundness, flatness and sphericity.

e) A mean B-axis of a specified number of the coarsest clasts

f) A median B-axis clast size.

g) The Trask (1952) sorting coefficient.

h) A calculation of the Zingg (1935) shape for each clast and a combined tabulation of Zingg (1935) shape and lithologic category.

A number of small modifications were made to the original program. (Appendix 1)

1) An error in the equation for skewness was corrected.

2) The following equation for sphericity (S) was substituted;

$$S = (C^2/A+B)^{0.333}$$

This is the maximum projection sphericity of Sneed and Folk (1958), which they suggested represents a good approximation of sphericity with respect to particle settling.

3) The sample distribution by size classes was altered from 8 - 1054mm to 2 - 512mm in accordance with the observed particle sizes in the current study.

Whilst Church (1970) argued that means directly obtained from the millimetre measures provided a good estimation of gravel particle size, it was observed that the existence of a few large clasts in any sample might displace the calculated mean grain size towards the coarser grades. Thus an adaption of the original program was made (Appendix 2), in which the raw data were transformed to $\log_2$ using the standard conversion.

$$\log_e D \times 1{\cdot}443$$

where;
D = Grain size measurement in mm
e = Base of natural logarithms

Hence, the moment measures obtained from the rewritten program represent phi-moment measures. This transformation was used incorrectly by Church (1970) to obtain a phi conversion of the calculated millimetre moment measures in the original program. In the current study the phi-moment measures were converted to mm to facilitate further analysis.

A comparison of the means calculated directly from the raw data and those calculated after the phi conversion indicated that the means calculated by the former method were biased towards the coarser values.

Wolman (1954) advocated the use of a graphical method for obtaining the moment measures in which phi grain size is plotted against the cumulative percentage by number of clasts in each phi grain size category. A comparison of a small number of means obtained graphically and by computation of moments using the modified Church (1970) program, indicates little difference in the results (Appendix 3). Any variance between the two methods may be possibly accounted for by the inaccuracies involved in graphical plotting and the low precision of graphically derived moment measures (Folk 1966).

The sample data were, therefore, analysed by the original program (Appendix 1) to obtain measures such as mean roundness, and by the adapted program (Appendix 2) to obtain moment measures for particle size. Each sample was also subdivided into two lithological groups;

1) Limestones and limestone/dolomite
2) Quartzites, sandstones and conglomerates.

These sub-groups were also analysed to obtain measures for the separate lithological categories.

In the subsequent statistical analysis the following measures obtained from the two programs were used.

1) Phi mean B-axis for the whole sample and the lithological subdivisions, with conversion into mm.

2) Phi standard deviation of the B-axis distribution.

3) Mean clast roundness

4) Mean clast flatness

5) Mean clast sphericity

6) The relative percentages of the two lithological categories.

7) The relative percentages of the various Zingg (1935) shape classes.

A number of alternative measures have been adopted to characterise particle size, although in field studies the B axis has been the most commonly used (Fahnestock 1963, Smith N.D. 1974). Unrug (1957) and Boothroyd and Ashley (1975), however, used the A axis and the measure (A+B+C)/3 has been recommended by Muir (1969). Koster *et al.* (1980), in a comparison of various measures, found that A, B, C, (A+C)/2, and (A+B+C)/3 were all subject to error in estimating clast nominal diameter. The magnitude of the error is related to the degree of shape variation. They concluded that $(ABC)^{1/3}$ was a superior measure, but endorsed B as an acceptable predictor of nominal diameter, although overestimating it when particle shapes were oblate or underestimating it when particle shapes were prolate. As no paleohydraulic reconstruction was attempted in this study the B axis was adopted as the measure of size in common with other field studies.

The use of the Zingg (1935) classification has been criticised by Sneed and Folk (1958). They stated that it is insufficiently precise for accurate determination of particle form, and showed that the classification poorly divided the field of variation of natural clast forms. They proposed a triordinate system with three main form categories, prolote, elongate, and compact, each further divided into sub-categories, for example, very elongate, compact prolate. This method was used by Bradley *et al.* (1972). However, Church (1972) and Koster *et al.* (1980) made use of the Zingg (1935) system. This system was used in the present study, despite the advantages of the Sneed and Folk

(1958) classification, as the calculated class percentages were readily available from the Church (1970) program.

The statistical analyses, outlined in Chapter Four were carried out using the Statistical Package for the Social Sciences (Edition 9) available through the University of Alberta computing system.

3.5 Map Construction

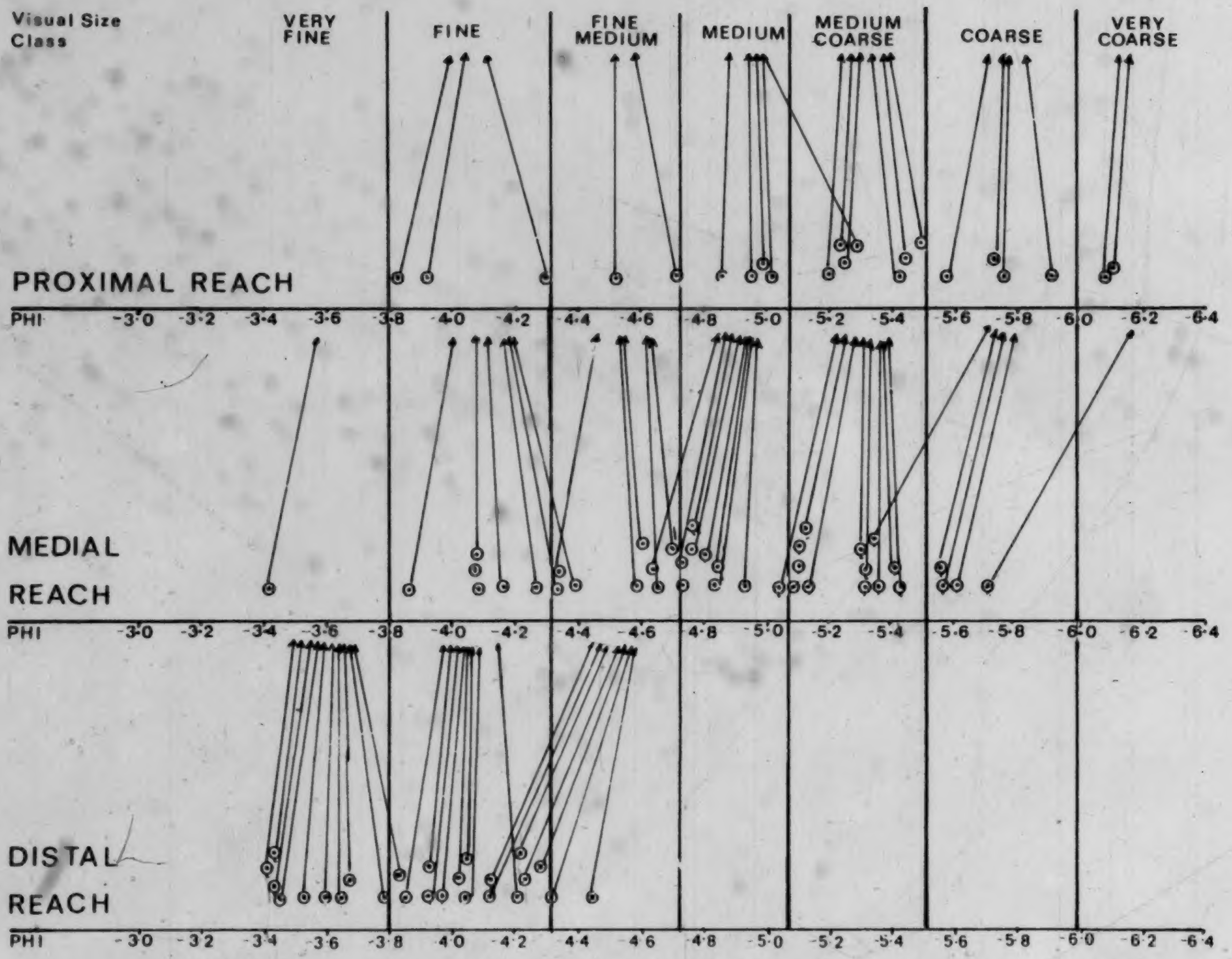
A mean grain size in phi units was calculated for the samples taken from the bar surfaces, after converting individual measurements into phi units. A comparison of the visual size classification and the calculated means was made to check the validity of the visual size classification (Fig 3.1). Two features may be noted.

1) Approximately 10-12 percent of the samples were misclassified according to mean grain size. Of these only 5 percent were seriously misclassified: i.e. were assigned to an adjacent coarser or finer category to that containing the mean grain size. The other misclassifications occurred when the sample mean grain size indicated that the sample was marginal to the assigned category. No sample was misclassified by more than one visual size grade.

2) The breaks between the visual size classes, as indicated by the mean grain sizes were very similar, within 0.1 phi for all three mapped areas. On the basis of the low percentage of misclassified samples over the three mapped areas, it was assumed that other visually classified, but unsampled areas were reliable.

On the maps (Figs 5.1, 5.2, 5.4), each size category was assigned an individual grey tone. Two additional tones were added for sand grade deposits and for areas of patchy fine gravel and sand. An important feature of the maps is that the prime objective in the original field mapping was the delimitation of individual gravel sheets rather than morphological mapping. The gravel sheets often extend to the base of individual gravel lobes. Hence, there is a seeming departure from conventional cartographic practice in that the scarp symbols are on the upslope side of the lines delimiting features.

COMPARISON OF VISUAL SIZE GRADES WITH MEAN GRAIN SIZES FIG. 3.1



4. DOWNSTREAM VARIATIONS IN SEDIMENTS

4.1 Variations in Size

4.1.1 Initial Analysis

Mean grain size when plotted as a function of distance (Fig 4.1), shows two distinct trends over the studied reach, with a marked break occurring at the Diadem Creek alluvial fan. Consequently, in the statistical analyses the proximal, medial and distal sub-reaches and the interfan sub-reach were treated separately. It should be noted that only the gravel samples, and not the sand samples, were subjected to the statistical procedures, as the two sample types cannot be used together in, for instance, analysis of variance procedures. The means obtained from the sand samples appear on certain of the graphical plots for the sake of completeness.

4.1.1.1 Analysis of Variance

Whilst the graphical plot (Fig 4.1) clearly indicates a highly significant change in grain size with distance, both up and downstream of Diadem Creek, these changes were tested for statistical validity. Three components of variation were defined within the sample data.

1) Within-sample variation.

2) Within-transect variation.

3) Downstream variation, between transects. The following null hypotheses were formulated:

> "a) Within-transect variance is significantly greater than within-sample variance. If so some factor, not defined, may be causing lateral variation over the study reach.
>
> b) Variance within the transects is significantly greater than variance downstream. If so, there is no basis for seeking any relationship describing changes in particle size downstream."

These hypotheses were tested using a hierarchical (nested) analysis of variance. Johnson and Leone (1964) outlined a number of assumptions that must be satisfied before the use

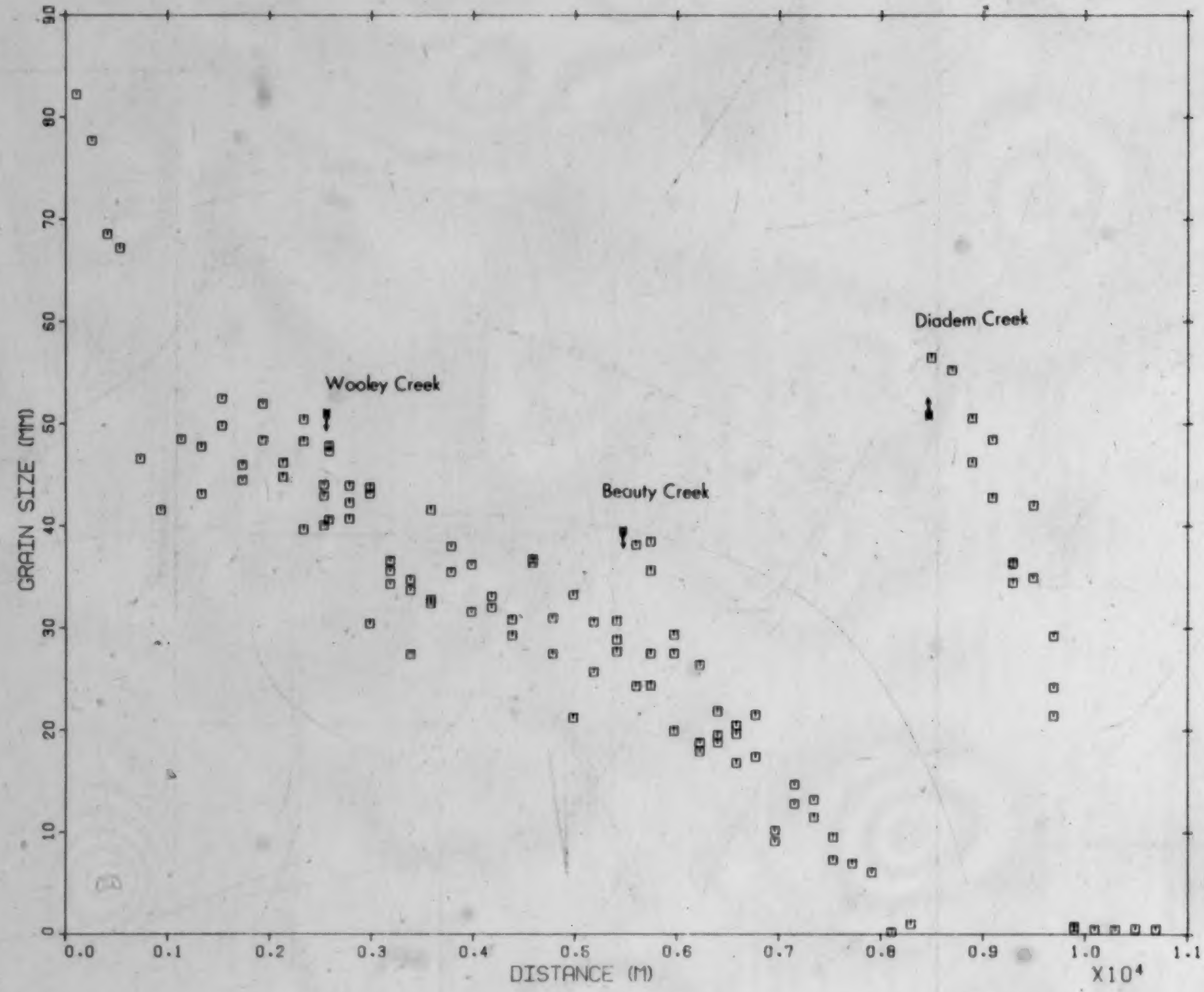


FIG. 4.1 MEAN GRAIN SIZES

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of such a model.

1) The expected value of each residual random variable is zero.

2) The residual random variables are mutually independent.

3) The residual random variables all have the same standard deviation, an assumption of homoscedascity.

4) The residual random variables are normally distributed.

Whilst the grain size data satisfy the first two conditions, as Church and Kellerhals (1978) noted, particle size distributions frequently exhibit variance proportional to the mean. This tendency is strongly evident in the Sunwapta River data. Church and Kellerhals (1978) suggested that if the data were transformed logarithmically (base e) constant variance would be achieved. The transformed data were tested for homogeneity of variances using Bartlett's test. This test indicated that for both the defined reaches there is a highly homogeneous set of data.

Although the original data is strongly positively skewed, and the transformed data, negatively skewed, no allowance for this was made in the analysis, as skewness was not regarded as being critical by Johnson and Leone (1964).

The formal model for the component of variance may be expressed as;

$$D_{rij} = \bar{D} + u_r + v_{ri} + z_{rij}$$

D_{rij} = an individual grain measurement
$\bar{D}$ = mean size of all sampled clasts.
u_r = component of variance between transects.
v_{ri} = component of variance within transects
z_{rij} = component of variance within samples.

Table 4.1 shows the results of the analyses. Null hypothesis (a) is accepted in both cases as the within-transect variance is significantly greater than the variance within the individual samples. However, null hypothesis (b) is rejected in both cases, as the variance between transects is significantly greater than the variance within a transect. Hence there exists a basis for seeking systematic variation in grain size downstream.

4.1.1.2 Regression

The form of the grain size variation was tested using least squares regression. As previously mentioned, theoretical and field studies show that particle size in relation to distance may be described by the following exponential equation:

TABLE 4.1 ANALYSIS OF VARIANCE OF SAMPLED DATA.

Proximal, Medial and Distal subreaches combined

Source of Variance	df	Sums of Squares	Mean Square	F	Sig
Between Transects	40	2102.98	57.57	29.65	0.00
Within Transects	47	83.35	1.77	8.73	0.00
Within Samples	8698	1767.95	0.203	-----	-----

Inter-fan sub-reach

Between Transects	6	104.29	17.38	15.41	0.001
Within Transects	7	7.89	1.12	6.25	0.00
Within Samples	1386	250.00	0.180	-----	-----

Critical significance value for rejection in all tables >0.05.

$$D = D_0 e^{-a_D x} \qquad \text{Equation 2}$$

D = a characteristic particle diameter.
x = distance downstream
a_D = coefficient of size diminution.

A first order, linear regression was therefore calculated, the relation between the two variables taking the form;

$$Ln\ D = a_D x + B + E \qquad \text{Equation 8}$$

Ln = base of natural logarithms
D = characteristic particle diameter
a_D = coefficient of size diminution.
x = distance
B = constant (intercept term)
E = error

Mather (1976) outlined the following assumptions involved in the use of least squares regression.

1) The mean of the error is zero

2) The variance of the error is constant at each level of the explanatory variable – the data is homoscedastic.

Both these assumptions are satisfied by the data sets under consideration.

3) The explanatory variable is non random and is measured without error. This assumption is not completely satisfied by the data in question, for, as previously noted, some error was introduced in delimiting the sampling transects. However, it is felt that, given the known, limited, magnitude of this error, the use of regression techniques is valid, and that a full functional analysis (Mark and Church 1977) is not necessary. A similar conclusion was reached by Church and Kellerhals (1978).

4) The values of E are independent of each other. This is an assumption that the observations are not autocorrelated.

Given that that there is more than one sample on most transects, and accepting that each sample yielded a meaningful measurement of grain size, variance in the data sets is attributed to three sources.

1) The relationship with distance.

2) Variance about the relationship.

3) Within-transect variance. This is treated as the residual variance.

Following the analysis of Williams (1959) the following null hypothesis was formulated.

> "Variance about the relationship is significantly larger than the within-site variance. If so, the relationship between grain size and distance is not adequately represented by the function $\ln D = a_D x + B + E$"

The results of the analysis are shown in Table 4.2. In both cases the regressions are highly significant. However, Table 4.2 shows that the deviations from the regression of mean grain size as a function of distance for the proximal, medial and distal sub-reaches are also highly significant. This is not the case for the regression of mean grain size as a function of distance for the inter-fan sub-reach. On the basis of these results it was concluded that some factor other than within-transect variation was causing variability in the data over the proximal, medial and distal sub-reaches. A major difference between the two regressed data sets is that there are multiple inputs of sediment into the study area upstream of Diadem Creek. Thus it was proposed to test whether these different sediment sources contribute to the variability in the data.

4.1.1.3 Analysis of Covariance

Analysis of covariance is a technique that combines the features of analysis of variance and regression. It allows interval scaled independent variables (covariates) to be used in conjunction with categorical variables (factors). The assumptions of the technique are similar to those of analysis of variance and regression. The purpose of such a technique is to determine whether a factor introduces significant variability into a relationship while controlling for a covariate by regression. A one-way analysis of covariance with one covariate may be expressed as follows.

TABLE 4.2 ANALYSIS OF VARIANCE OF SIZE-DISTANCE REGRESSION

Proximal, Medial and Distal sub-reaches combined

Source of Variance	df	Sums of Squares	Mean Square	F	Sig
Regression	1	17.37	17.37	147.87	0.00
Deviation from Regression	39	4.58	0.117	6.64	0.00
Between Transects	40	21.03	0.526	29.71	0.00
Within Transects	47	0.833	0.017	-----	-----

Inter-fan sub-reach

Regression	1	0.904	0.904	20.98	0.00
Deviation from Regression	5	0.215	0.043	3.82	>0.05
Between Transects	6	1.043	0.174	15.42	-0.00
Within Transects	7	0.079	0.011	-----	-----

$$Y_{ijk} = \mu + \alpha_i + B(X_{ijk} - \bar{X}) + E_{ijk}$$ (Nie and Hull 1982)

Y_{ijk} = dependent variable
α_i = categorical factor
X = covariate
$\bar{X}$ = mean of the covariate
μ = constant
B = regression coefficient
E = error

The samples were catagorised by position in the proximal, medial or distal sub-reaches. This formed the factor, with three levels, in the analysis. Distance was the covariate. The following null hypothesis was formulated:

> "The sample position according to sub-reach introduces no significant variability into the sampled mean grain size over the study reach, when the effects of distance are controlled."

The results of the analysis are shown in Table 4.3. The null hypothesis was rejected at a significance level of 95 percent. Hence it may be suggested that the separate inputs of sediment from the two tributaries in the reach, upstream of Diadem Creek, also affect grain size relationships.

4.1.1.4 Summary

Two sources of variability around the relationships between grain size and distance, were indicated by the initial statistical analyses.

1) Variability within individual sample transects across the reach.

2) Variability introduced by tributary inputs. This is most marked at the Diadem Creek alluvial fan. However, statistical analysis also suggests that the other, smaller, tributaries have their effects.

4.1.2 Within-transect Variability

Two possible sources of within-transect variability were identified.

4.1.2.1 Position of the Sample Across the Reach

Bradley *et al* (1972) suggested that inputs from tributaries and bedrock sources are poorly mixed across a braided outwash. Hence, relatively coarse or fine material may be preferentially located to one or other side of the reach. The samples were classified during the initial sampling according to their position on the transects - east or west.

TABLE 4.3 ANALYSIS OF COVARIANCE OF SIZE-DISTANCE RELATIONSHIPS

Proximal, Medial and Distal sub-reaches combined

Source of Variance	df	Sums of Squares	Mean Square	F	Sig
Regression	1	4.365	4.365	86.30	0.00
Constant	1	60.73	60.73	1200.75	0.00
Position according to reach	2	0.417	0.208	4.12	0.02
Within Cells	84	4.248	0.051	-----	-----

Thus the mean grain sizes of the samples may be separated into two groups according to their lateral position. Samples taken centrally along a transect are not included. The two groups form two "grand" samples representing grain sizes to the west and east sides of the active valley train. In order to eliminate distance effects only those mean grain sizes obtained from the medial sub-reach were used, as this was the only sub-reach in which complete pairs of samples were obtained.

To test for differences between the two "grand" samples a Student's T-test was performed. The following null hypothesis was formulated;

> "There is no significant difference in the sampled mean grain sizes, classified according to their lateral position in the studied reach."

The significance level was set at 95 percent.

The results of the analysis are shown in Table 4.4. An important assumption of Student's T-test is that the two samples should have approximately equal variances. An F-test was performed on the variances of the two grand samples. This showed that the variances were not significantly different at the 95 percent level. The results of this test showed no significant difference between the two "grand" means and hence the null hypothesis was accepted.

4.1.2.2 Size of Adjacent Channel

The samples were also classified according to whether they had been taken adjacent to a major or minor channel. The assessment of channel size was based on their width. The same samples used in the previous analysis, with the addition of six samples taken centrally in the reach, were thus reclassified into two "grand" samples based on relative channel size.

A T-test was performed on the two "grand" samples with the following null hypothesis being formulated;

> "There is no significant difference in the sampled mean grain sizes classified according to adjacent channel size."

The significance level was set at 95 percent.

The results of the analysis are shown in Table 4.5. An F-test on the variances of the two "grand" samples showed that they were not significantly different at the 95 percent level. The results of the test show no significant difference between the two

TABLE 4.4. T-TEST ON SAMPLE MEAN GRAIN SIZES CLASSIFIED ACCORDING TO POSITION ACROSS THE MEDIAL SUB-REACH.

	No. of Cases	Mean	S.D	S.E	F	Prob	T	df	Prob
West Samples	14	32.76	5.59	1.49	1.04	0.94	-1.1	26	0.28
East Samples	14	35.11	5.71	1.53					

TABLE 4.5. T-TEST ON SAMPLE MEAN GRAIN SIZES CLASSIFIED ACCORDING TO ADJACENT CHANNEL SIZES

	No. of Cases	Mean	S.D	S.E	F	Prob	T	df	Prob
Major Channel	16	35.83	5.35	1.34	1.67	0.33	0.53	31	0.60
Minor Channel	18	34.71	6.93	1.63					

"grand" means and hence the null hypothesis was accepted.

The source of the significant variability within individual transects is thus undefined, according to the two above factors. As Church and Kellerhals (1978) noted a number of factors may contribute to grain size variation at a site. Examples of these are flows secondary and transverse to the main channel flow and discontinuous movements of sediment, which may be random and not easily defined. Local variation in grain size is examined in greater detail in Chapter Five.

4.1.3 Downstream Variation about the Size-Distance Relationship

4.1.3.1 Tributary Effects

Trends in grain size over the reach are most markedly affected by the input of coarse debris at the Diadem Creek alluvial fan. Similar tributary effects have been noted by Smith D.G. (1971), Church and Kellerhals (1978), Knighton (1980, 1982), Shaw and Kellerhals (in press). The effects of this tributary may be summarised as follows;

1) grain size increases from less than 2mm to approximately 65mm.

2) slope increases, immediately downstream of the fan.

3) the fan acts as a local base level, causing an upstream reduction in water surface slope.

If a single regression of grain size as a function of distance had been calculated for the complete data set, this tributary would have introduced variability around the regression and would have been recognisable as a local increase in the rate of overall diminution of grain size, as noted by Church and Kellerhals (1978). It may be concluded that where the sediments contributed by a tributary are coarser than those in the main channel, a separate diminution curve for the tributary sediments is superimposed. For the tributary under examination, however, it should be noted that the volume of sediment contributed by the fan in part accentuates the difference in the sediment size downstream as compared to upstream by creating a backwater effect and reducing competence in the immediate upstream reach. A similar backwater effect occurs upstream of the unnamed fan at the downstream end of the study reach (Fig 1.2). Examination of the slope profile (Fig 1.4) suggests that this backwater curve extends upstream for approximately 1.6 km. In both the distal and inter-fan sub-reaches the reduced slopes have a similar effect- a reduction in competence with a corresponding small size of bed sediment. This is most markedly shown in the inter-fan sub-reach where there is a change both in grain size, from gravel (mean grain size approximately 30mm) to sand, and water surface slope around the headward limit of the backwater curve.

The analysis of covariance shows that the grain size varies between the sub-reaches upstream of Diadem Creek, after the effect of distance is controlled. In order to demonstrate this variability the residuals from the regression of size as a function of distance, for the samples upstream of Diadem Creek, were plotted against distance (Fig 4.2). To remove scatter about the relationship, introduced by within-transect variabilty, the residuals were averaged within each transect.

The effect of the two tributaries, Wooley Creek and Beauty Creek, as demonstrated by the plot of smoothed residuals, differs. Wooley Creek has little effect on the general relationship between grain size and distance. However, around the position of Beauty Creek the residuals are strongly positive, illustrating an input of coarser debris here. The limited effect of Wooley Creek on grain-size relationships is supported by geomorphic observation. The small alluvial fan constructed by this creek into the main reach is degraded and, consequently, there is unlikely to be a significant contribution of debris to the main channel. Both Wooley Creek and Beauty Creek influence the water surface profile in a similar but less pronounced fashion to Diadem Creek, with a flattening of the profile upstream and a steepening downstream. The change in the water surface profile at Wooley Creek is unexpected given the limited effect of the tributary on grain size, and may be a residual effect from the earlier aggradation of the alluvial fan or be related to the lateral confinement of the reach at this point.

4.1.3.2 Other Effects

The plot of the smoothed residuals from the regression of size as a function of distance for the proximal, medial and distal sub-reaches also demonstrates two other areas where high residual values occur. Downstream of Beauty Creek, the residuals show a rapid change from positive to negative with distance. This strongly suggests an alternative relationship between grain size and distance than described by the regression,

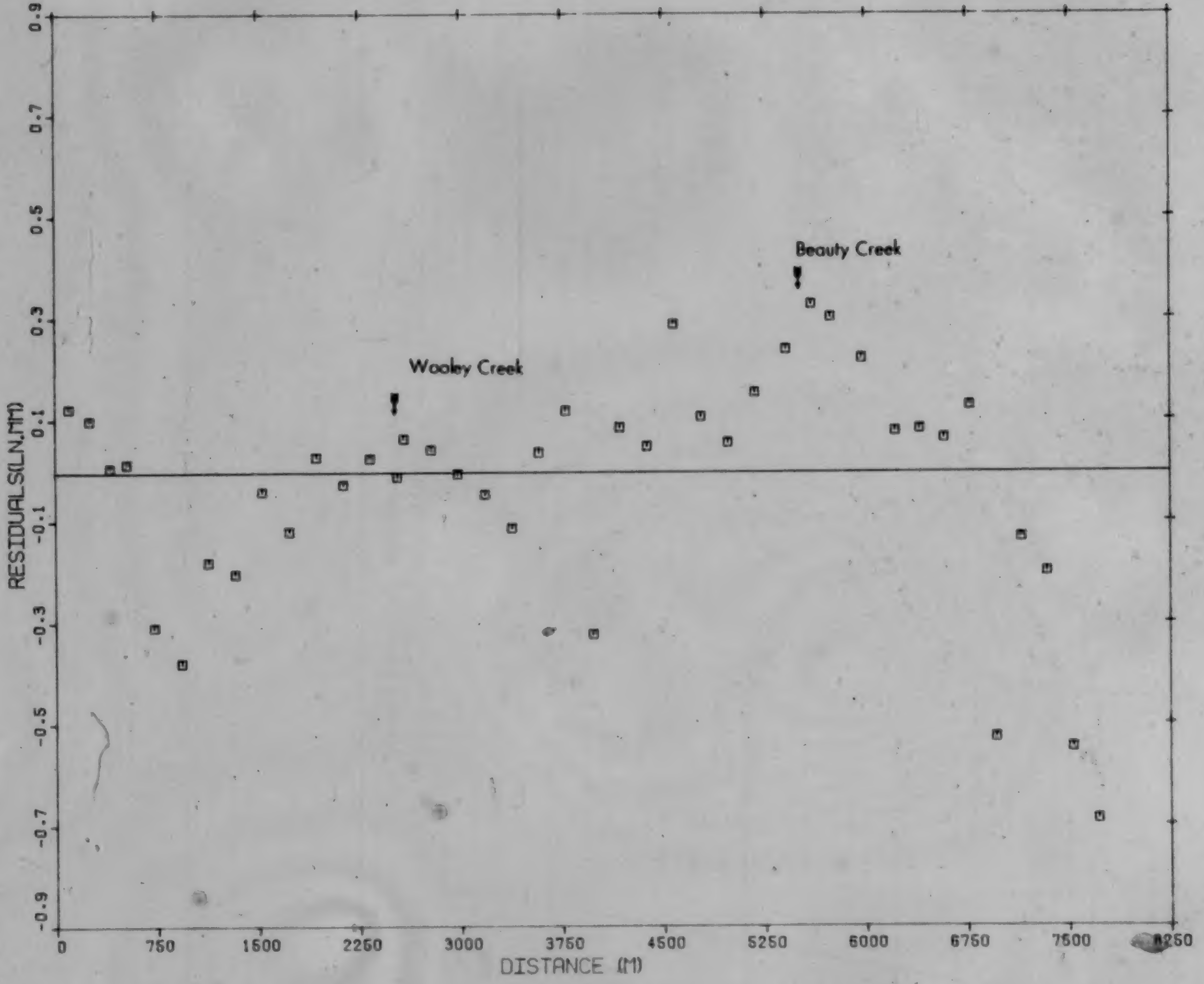

FIG. 4.2 SMOOTHED RESIDUALS FROM THE SIZE-DISTANCE REGRESSION

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and represents an increase in the rate of diminution. This change is also evident on the semi-logarithmic plot of grain size versus distance (Fig 4.1).

For the proximal sub-reach the residuals from the regression for the samples located between 750 m and 2000 m (from the head of the reach) are markedly negative, indicating a finer grain size than predicted by the overall relationship. Fig 4.2 shows an initial, rapid, decline in grain size as expected from the theoretical exponential relationship, but after 750 m there is no marked decline.. Whilst this anomaly may result from the limited number of samples taken in the area, it was also observed qualitatively during the field investigation.

The rapid initial decline of grain size, followed by the relatively constant trend in grain size shown by the samples taken from the proximal sub-reach, may be possibly the result of differential aggradation and degradation. The proximal sub-reach, as previously described (Chapter 1), comprises a single main channel for approximately 400 m, after which braiding commences, with the main, braided course being confined to the western edge of the reach. The existence of a small terrace demarcating the eastern edge of the active braided flats, and an east to west slope to the valley floor (Rice 1979), indicate that the reach is undergoing limited degradation. The observed pattern of grain size change with distance seems to be the result of two factors;

1) The initial decline in grain size may be related to a decline in competence with distance along the single main channel, and, more particularly with the commencement of braiding. This results in deposition of relatively fine sediments in the upper portions of the braided reach.

2) The subsequent increase in grain size further downsteam is possibly related to the reworking of coarser sediments, deposited during an earlier aggradational phase of the braided flats, by the currently degrading stream.

Immediately downstream of Beauty Creek the increased rate of diminution may be a function of a readjustment to the input of coarse debris and the slightly increased slope in the area. Further downstream the lower water surface slope, related to the backwater curve created by the Diadem Creek alluvial fan, results in a reduced competence. This allows only a smaller grain size to be transported and results in a rapid rate of size diminution around the break of water surface slope. The combination of grain size decline away from the tributary and the reduced competence in the backwater area may explain the rapid diminution of grain size through the distal sub-reach.

An alternative hypothesis can be proposed, based on the work of Rana *et al.* (1973). They reduced Einstein's (1950) bedload formula to two parameters; discharge intensity of flow ($m^3 s^{-1} m^{-1}$) and bed material load concentration (ppm) to show that for a constant bed material load concentration, a decrease in discharge intensity of flow results in an increased coefficient of size diminution. In a highly simplistic sense, introducing possibly untenable assumptions, a similar effect may be seen from the data of Rice (1979). Assuming that the average conditions in the Sunwapta River are directly comparable to the theoretical situation, and allowing for changes in average width, it may be seen (Table 4.6) that the discharge intensity of flow decreases from the middle to lower reaches. It should be noted that Rice (1979) observed changes in mean depth between adjacent reaches which further complicate a direct comparison. No allowance for the changes in mean depth is made here. Assuming a constant bed material load concentration, and a slope with an exponential form, it is predicted that the rate of grain size diminution would increase in the medial sub-reach as compared to the proximal sub-reach and in the distal sub-reach as compared to the medial sub-reach. The latter effect is observable from the semi-logarithmic plot of grain size as a function of distance (Fig 4.3).

4.1.4 Diminution Rates

From the regressions of the form $\ln D = a_D x + B + E$, presented previously, diminution coefficients were obtained for the proximal, medial and distal and inter-fan portions of the study reach. As significant variation occurs between the proximal, medial and distal sub-reaches, separate regressions were obtained for each sub-reach. Previous flume and field studies (Kuenen 1956, Bradley 1970) have shown that rates of diminution under conditions of attrition vary between lithologies. For instance, limestones have been shown to be considerably less resistant to abrasion than quartzites or granites. Consequently, the samples were divided into two lithological categories, limestone and quartzitic, and separate regressions were run for each of the reaches and sub-reaches. As previously described the quartzitic category comprised quartzites, quartzitic

TABLE 4.6. VARIATIONS IN AVERAGE CHANNEL DISCHARGES
(Data from Rice 1979)

Reach	Av Q m^3	Width m	$m^3/s/m$
Proximal	3.27	8.10	0.404
Medial	2.14	7.63	0.281
Distal	2.02	8.41	0.240

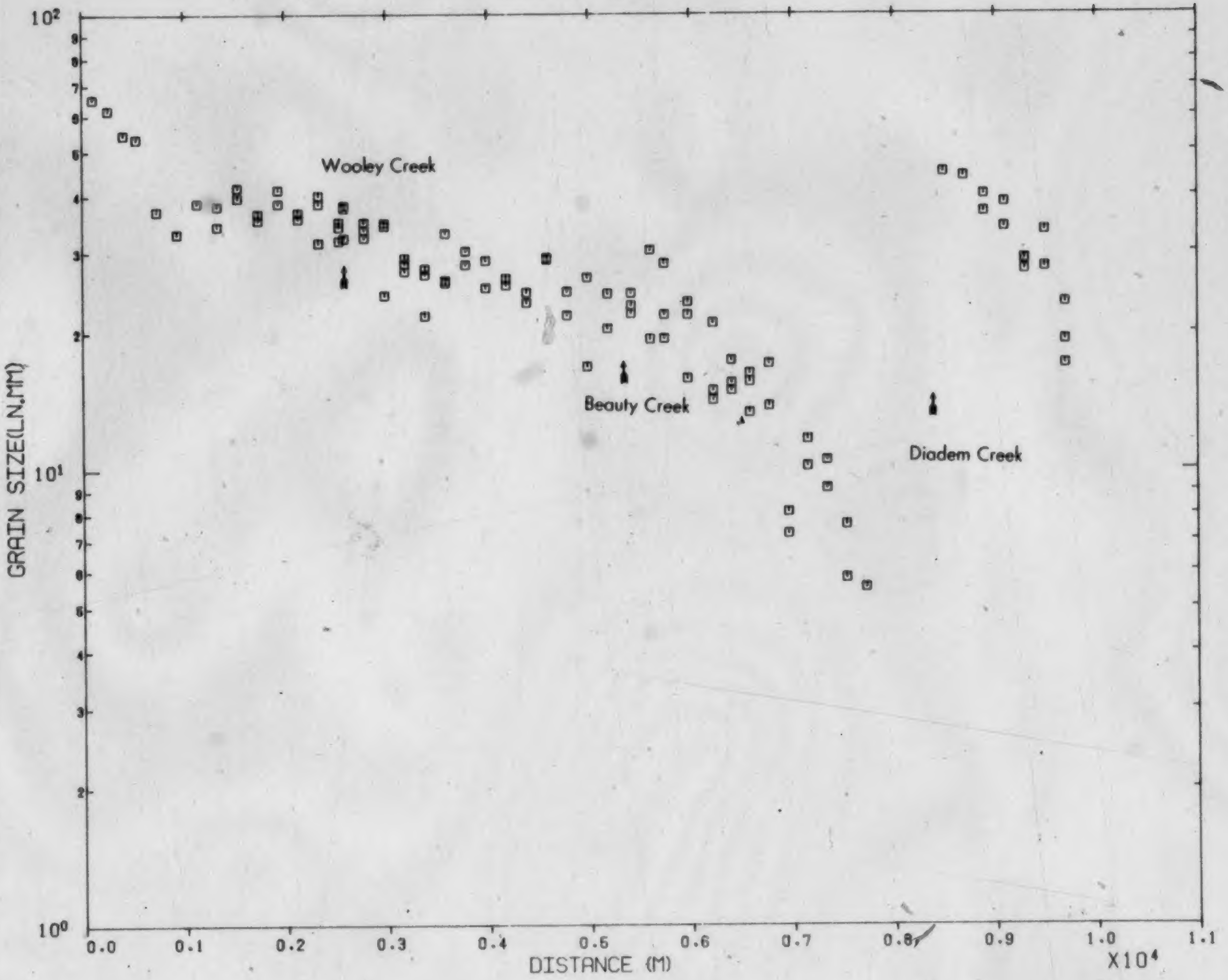

FIG. 4.3 LOG. GRAIN SIZES

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sandstones, and quartzitic conglomerates. All these lithologies showed varying degrees of metamorphism and were expected to abrade similarly under conditions of transport. As shown in Appendix 4 all the regressions are highly significant with high R^2 values. The diminution coefficients obtained from the regressions are presented in Table 4.7.

The diminution coefficients are highest in the inter-fan sub-reach and lowest in the proximal sub-reach. There is an increase in the rate of diminution between the proximal and medial sub-reaches and more markedly between the medial and distal sub-reaches. Some explanation of these changes in the diminution coefficients has already been presented. The diminution coefficients for the quartzitic group of lithologies are consistently higher than those demonstrated by the limestones throughout the data set, however divided. Such differences are anomalous as previous work (Kuenen 1956, Shaw and Kellerhals in press) has shown that quartzites have lower diminution coefficients than limestones. The consistently higher diminution coefficients for the quartzitic lithological group were felt to be a product of the grouping of quartzites, sandstones and conglomerates. Consequently, separate size distance regressions were run on sub samples of the true quartzite clasts only. The analysis was hindered by the low numbers, generally less than 20, of the true quartzite clasts in the samples. In order to obtain a representative mean size from each sample, only those samples with at least 10 clasts were used in the regression analysis. This produced a sample population of 50 all located upstream of Diadem Creek, predominantly in the medial and distal sub-reaches. Only five samples were located in the proximal sub-reach.

Three regressions of size as a function of distance were calculated. Table 4.7 shows that for the two significant regressions the diminution coefficients are, like those obtained for the quartzitic lithological group, higher than those obtained for the limestones.

The statistical significance of the difference between the diminution coefficients for the limestones and the quartzitic lithologies and the limestones and the quartzites were tested using a procedure outlined by Kleinbaum and Kupper (1978) to see whether the slopes of the respective regressions were significantly non-parallel. The calculations and results of these tests are outlined in Appendix 5 and show that in all cases there is

TABLE 4.7 DIMINUTION COEFFICIENTS: SUNWAPTA RIVER

		km^{-1}
Proximal, Medial and Distal	Total Sample	0.02180
	Limestone	0.02149
	Quartzitic	0.02278
	Quartzite	0.02532
Proximal	Total Sample	0.01578
	Limestone	0.01537
	Quartzitic	0.01848
Medial	Total Sample	0.01943
	Limestone	0.01781
	Quartzitic	0.02440
Distal	Total Sample	0.06057
	Limestone	0.05899
	Quartzitic	0.06348
	Quartzite	0.06618
Inter-fan	Total Sample	0.06919
	Limestone	0.06466
	Quartzitic	0.07233

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no basis for assuming that the diminution coefficients are significantly different. The implications of this test are that the difference in the diminution coefficients may be completely accounted for by the variability in the data. This may be a factor in other studies but has been previously unreported.

The relative contribution of differential transport and attrition may be assessed by directly comparing the coefficients obtained from previous studies. Shaw and Kellerhals (in press) obtained diminution coefficients for the central reaches of the Athabasca, North Saskatchewan, Red Deer and Bow-South Saskatchewan Rivers. On geomorphic grounds they argued that the central reaches of these rivers in Alberta are undergoing net degradation and hence size diminution should be explained by attrition. Attrition was divided into two components, attrition *in situ* and attrition in transport. Assuming that rates of attrition are similar in both aggrading and degrading situations, the proportion of size diminution accounted for by differential transport may be obtained (Bradley *et al.* 1972). A direct comparison between the Sunwapta River and the others is justified on the grounds that all the rivers rise in the same geologic region. Furthermore the Sunwapta River is a major tributary of the Athabasca system.

However, the assumption that rates of attrition in aggrading and degrading situations are similar may be incorrect. Shaw and Kellerhals (in press) noted that attrition *in situ* was the predominant mechanism causing size diminution due to the length of time clasts remain emplaced in the bed. In an aggrading situation the periods when clasts are exposed to attrition *in situ* may be reduced relative to time in transport, as compared to a degrading river. Unless the effectiveness of attrition in transport (if there is a greater frequency of transport), compensates for a probable reduction in the amount of attrition caused by *in situ* processes, the amount of size reduction accounted for by attrition as a whole in an aggrading situation should be less than a degrading one.

The coefficients obtained by Shaw and Kellerhals (in press) were averaged to provide a coefficient of diminution for limestones and quartzites under degrading conditions (Table 4.8). Table 4.9 shows the results of the comparison. It would be expected that given similar densities the proportion of the diminution coefficient attributable to transport would be similar for the limestones and quartzites. However, it may be seen that the proportion of the diminution coefficients due to transport are

TABLE 4.8 DIMINUTION COEFFICIENTS FROM OTHER ALBERTAN RIVERS (GRAVEL BEDDED SECTIONS THROUGH THE PLAINS)

Shaw and Kellerhals (in press)

River	Diminution Coefficients	
	Quartzites	Limestones
	km^{-1}	km^{-1}
North Saskatchewan	0.00169	0.0097
Red Deer	0.00350	0.0118
Bow S.Saskatchewan	0.00169	-------
Athabasca	-------	0.0119
Mean	0.00229	0.0113

TABLE 4.9 COMPARISON OF THE DIMINUTION COEFFICIENTS FROM THE SUNWAPTA RIVER AGAINST THE AVERAGE LOCAL DIMINUTION COEFFICIENTS OBTAINED BY SHAW AND KELLERHALS (IN PRESS)

	LIMESTONE		QUARTZITE	
Reach	Diminution due to diff. transport	Diminution due to attrition	Diminution due to diff. transport	Diminution due to attrition
	km	km	km	km
Proximal Medial Distal	0.01148	0.0113 47.4%	0.02303	0.00229 9.0%
Inter-Fan	0.05316	0.0113 17.5%	N.S.	
Proximal	0.00407	0.0113 73.5%	N.S.	
Medial	0.00651	0.0113 63.4%	N.S.	
Distal	0.04769	0.0113 19.1%	0.0661	0.00229 3.5%

consistently higher for quartzites. Two possibilities may account for these differences. First, there may be an element of shape sorting. Lane and Carlson (1954) noted that differences in shape outweighed the effects of different density under conditions of differential transport. This possibility will be discussed in detail when variations in shape are examined. Secondly, there may be lithological differences between the limestones and quartzites of the Sunwapta River and those considered by Shaw and Kellerhals (in press).

The variation of the diminution coefficients for limestones between sub-reaches seems to show that different rates of aggradation and degradation are occurring in the Sunwapta River. The relatively small contributions of differential transport to the diminution coefficient in the proximal and medial sub-reaches suggest that the sediment in transport is merely being reworked, and that the reaches are undergoing net degradation. This contention is supported by the existence of terraces in both the proximal and medial sub-reaches. The higher rates of diminution in the distal and inter-fan sub-reaches suggest that these may still be aggrading, with the distal sub-reach receiving sediments from upstream and the inter-fan sub-reach receiving sediment eroded from the Diadem Creek alluvial fan and from Grizzly Creek. However, there was limited evidence of gravel transport in the inter-fan sub-reach and this high rate of diminution may be a residual effect from a period when the fan was actively aggrading.

Further comparison may be made between the diminution coefficients obtained from the Sunwapta River and those reported in other studies (Appendix 6). The coefficients calculated for the present study fall in a similar range to those established for rivers known to be aggrading. Examples are the Columbia River, British Columbia (Kellerhals, in Shaw and Kellerhals, in press) and some alluvial fans, for example those studied by Yatsu (1957) and Schlee (1957). The coefficients are in many cases lower than those found on rapidly aggrading fans (Blissenbach 1954), or fans thought to have aggraded rapidly (Bluck, 1965). However, as previously noted, the diminution coefficients are significantly higher than those obtained from rivers known to be degrading (Bradley 1970, Shaw and Kellerhals in press). In comparison to the diminution coefficient reported by Nordseth (1973) for a braided reach on the River Glomma, Norway, the coefficients from the Sunwapta River are lower, a possible reflection of a lower rate of aggradation or current degradation.

4.2 Downstream Variations in Sorting

The plot of phi standard deviation as a function of distance shows, like the size data, a discontinuity at the Diadem Creek alluvial fan (Fig 4.4). On these, and geomorphic grounds, two separate regressions were applied to the data. The results of the analysis are shown in Table 4.10 and indicate two highly significant linear trends.

Knighton (1980) proposed that variations in sorting in reaches with multiple tributaries are best described by a cosine function of the following form;

$$\sigma_\phi = \alpha + Ve^{-yx} \cos(wx - p) \qquad \text{Equation 9}$$

where;

σ_ϕ = phi standard deviation
α = average condition about which fluctuations take place.
V = amplitude of this variation about the mean value.
y = coefficient, the sign of which determines the behaviour of the amplitude downstream.
π/w = period of oscillation. $\pi = 3 \cdot 142$
p = phase angle.
x = distance.
e = base of natural logarithms.

Knighton (1980) argued that in the vicinity of a tributary introducing coarse debris, values of the sorting coefficient would increase, both immediately downstream and upstream of the tributary. The latter increase, he stated, would occur "as the effects of the tributary inflow migrate upstream" (Knighton 1980, p61).

This function is clearly inappropiate in the case of the Diadem Creek tributary, where the effect of the input of coarse sediment on sorting results in a separate linear decline. The residuals from the regression fitted to the data obtained from the reach above Diadem Creek were examined to see whether a cosine function was applicable. To remove the considerable variability in the data the residuals were averaged within each transect, and then plotted as a function of distance. Examination of this graph (Fig 4.5) indicates no systematic variation in the data, and the effects, if any, of the two tributaries are obscure. There is, however, evidence of an initial rapid improvement in sorting over the first kilometre of the proximal sub-reach. It is suggested, on the evidence presented above, that Knighton's (1980) alternative hypothesis describing improvements in sorting

TABLE 4.10 REGRESSIONS OF PHI S.D. ON DISTANCE DOWNSTREAM

Reach	R	R^2	Sig	B (Slope)
Proximal Medial Distal	-0.7413	0.5495	0.00	-0.000488
Inter-Fan	-0.8002	0.6403	0.00	-0.002336

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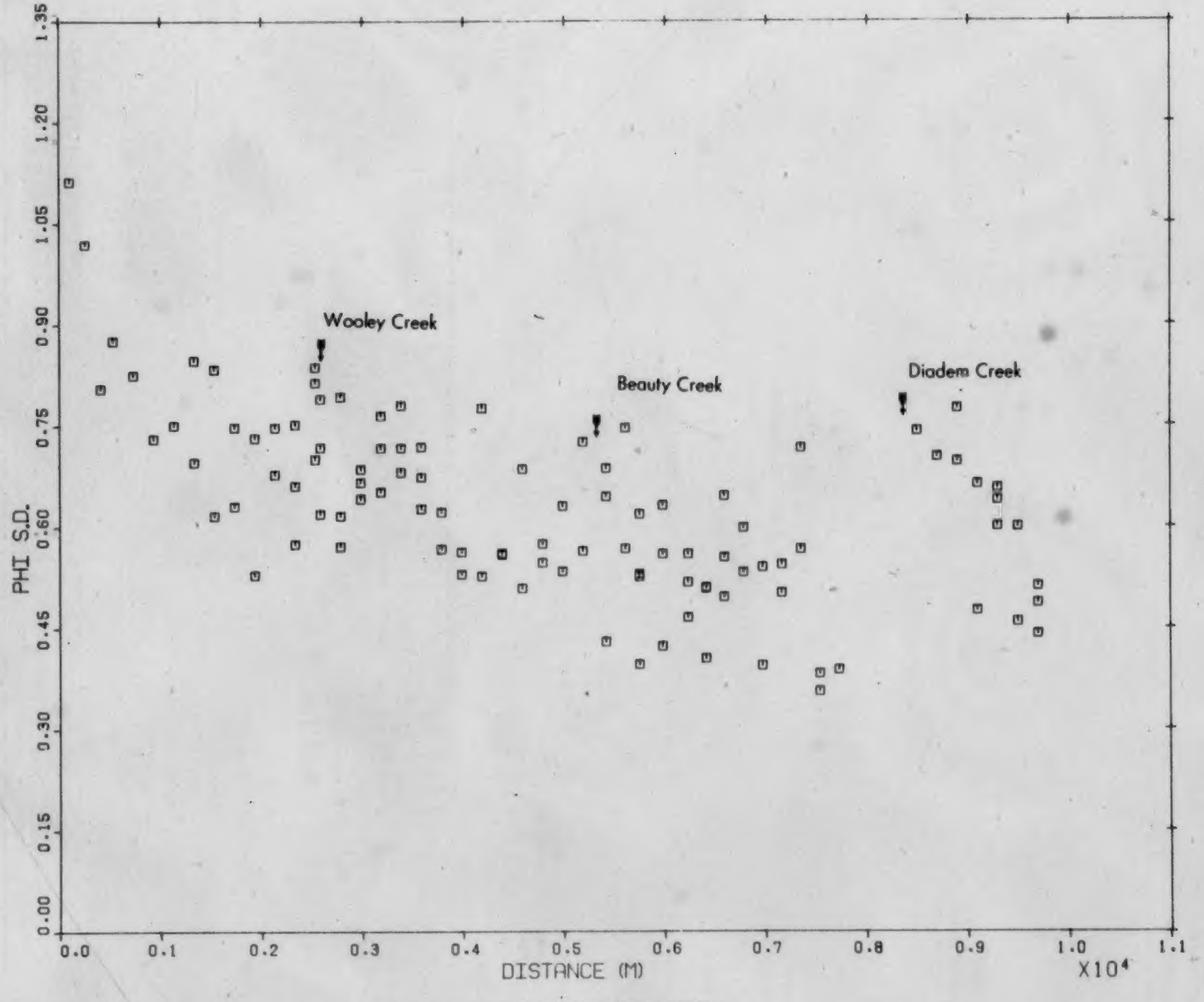

FIG. 4.4 PHI STANDARD DEVIATION

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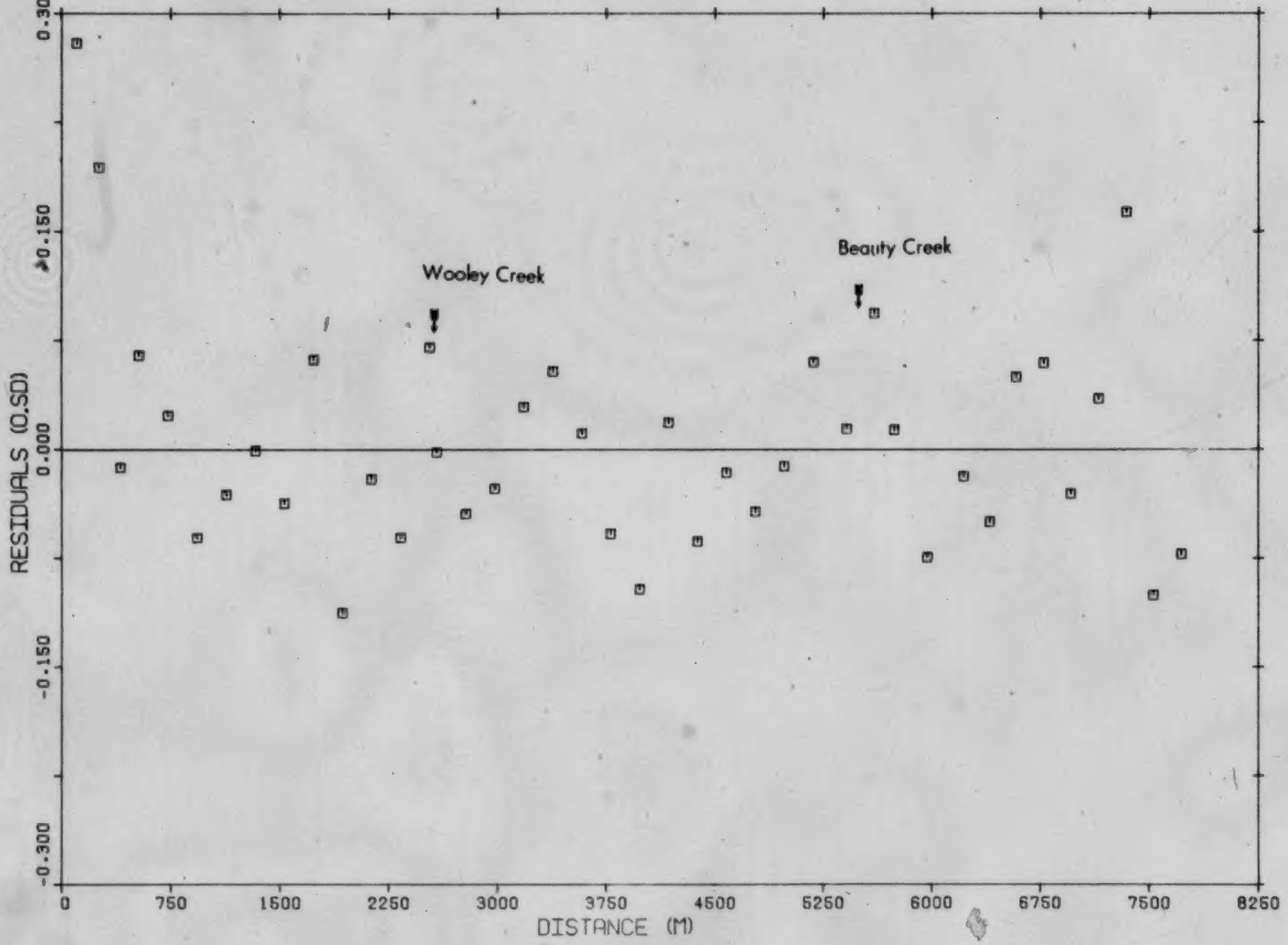


FIG. 4.5 SMOOTHED RESIDUALS FROM THE STANDARD DEVIATION-DISTANCE REGRESSION

away from tributaries as being separate exponential functions is more appropiate than a cosine function, there being no evidence of a cosine relationship being applicable for this reach of the Sunwapta River.

The graph of phi standard deviation against distance (Fig 4.4) shows considerable within-transect variability. A similar analysis to that performed on the size data was undertaken, by identifying two possible causes for within-transect variation; position across the reach; and the relative size of the adjacent channel. As with the size data the analysis was performed only on replicate samples from the medial sub-reach. The division of the data set was identical to that undertaken for the size data, with a T-test being performed on two "grand" samples.

1) Position across the reach.

The following null hypothesis was formulated;

> "There is no significant difference in the values of phi standard deviation, classified according to position across the reach"

The results of the analysis are shown in Table 4.11. An F-test on the variances of the two grand samples showed that they were not significantly different at the 95 percent level. The results of the T-test show that there is no significant difference between the two grand means and hence the null hypothesis was accepted.

2) Size of adjacent channel.

The following null hypothesis was formulated;

> "There is no significant difference in the values of phi standard deviation classified according to the size of the adjacent channel"

The results of the analysis are shown in Table 4.11 The F-test on the variances of the two "grand" samples indicated that they were not significantly different at the 95 percent level. The T-test shows that there is no significant difference between the two grand means and hence the null hypothesis was accepted.

As with the size data, no definite cause can be ascribed to the within-transect variabilty of the phi standard deviation values.

TABLE 4.11 RESULTS OF THE T-TEST GRAND MEANS OF THE GROUPED PHI STANDARD DEVIATIONS

	No. of Cases	Mean	S.E	F	Prob	T	df	Prob
East Samples	14	0.641	0.023	1.21	0.74	0.69	26	0.50
West Samples	14	0.619	0.021					

	No. of Cases	Mean	S.E	F	Prob	T	df	Prob
Major Channel	16	0.653	0.025	1.86	0.22	0.56	28	0.58
Minor Channel	18	0.636	0.017					

4.3 Downstream Variations in Particle Shape

Variations in particle shape were analysed in terms of four parameters; roundness, flatness, sphericity and Zingg (1935) axial ratios.

4.3.1 Clast Roundness

In common with size-distance relationships, trends in roundness show a marked break at the Diadem Creek alluvial fan, with gravel immediately downstream of the fan being less round than the gravel upstream. A similar effect was noted by Knighton (1982) for the River Noe, Derbyshire, England. Two separate linear regressions were, therefore, fitted to the data, although Krumbein (1942) and Plumley (1948) noted that downstream changes in roundness were best described by a relationship with two separate terms. Mills (1979) proposed that semi-logarithmic relationships provided a better description of downstream variations in roundness. However, such a relationship provided less explanation of the variability in the data than a linear regression upstream of Diadem Creek and only a marginal increase in the degree of explanation downstream of Diadem Creek. Examination of the graph of roundness as a function of distance (Fig 4.6) suggests that a relationship similar to those proposed by Krumbein (1942b) and Plumley (1948) exist in the Sunwapta River upstream of the Diadem Creek fan, there being a rapid increase in roundness over approximately the first kilometre, followed by a subsequent slower rate of increase downstream.

Both regressions were significant at the 95 percent level as shown in Table 4.12. Given that the Diadem Creek tributary introduces debris of lower roundness in comparison to the gravel in the immediate upstream reaches, an analysis of covariance was performed to see whether roundness varies between the sub-reaches upstream of the Diadem Creek fan, after allowing for distance effects. The analysis was similar to that performed in section 4.1 and the results are shown in Table 4.13.

After controlling for distance there is significant variability in roundness between the respective reaches. The form of this variation was examined by plotting the residuals from the regression of sample roundness, averaged within-transects against distance.(Fig 4.7) The plot of the smoothed residuals shows the initial rapid increase as being separate from the later general trend, again strongly suggesting that downstream variations in

TABLE 4.12 REGRESSIONS OF ROUNDNESS ON DISTANCE DOWNSTREAM

Reach	R	R^2	Sig	B (Slope)
Proximal Medial Distal	0.64683	0.41839	0.000	0.0000114
Inter-Fan	0.74098	0.54905	0.000	0.0000425

TABLE 4.13 ANALYSIS OF COVARIANCE OF ROUNDNESS-DISTANCE RELATIONSHIPS

Proximal, Medial and Distal sub-reaches combined

Source of Variance	df	Sums of Squares	Mean Square	F	Sig
Regression	1	0.0171	0.0171	26.39	0.00
Constant	1	0.9703	0.9703	1496.27	0.00
Position according to reach	2	0.0068	0.0034	4.23	0.007
Within Cells	85	0.0551	0.0065	-----	-----

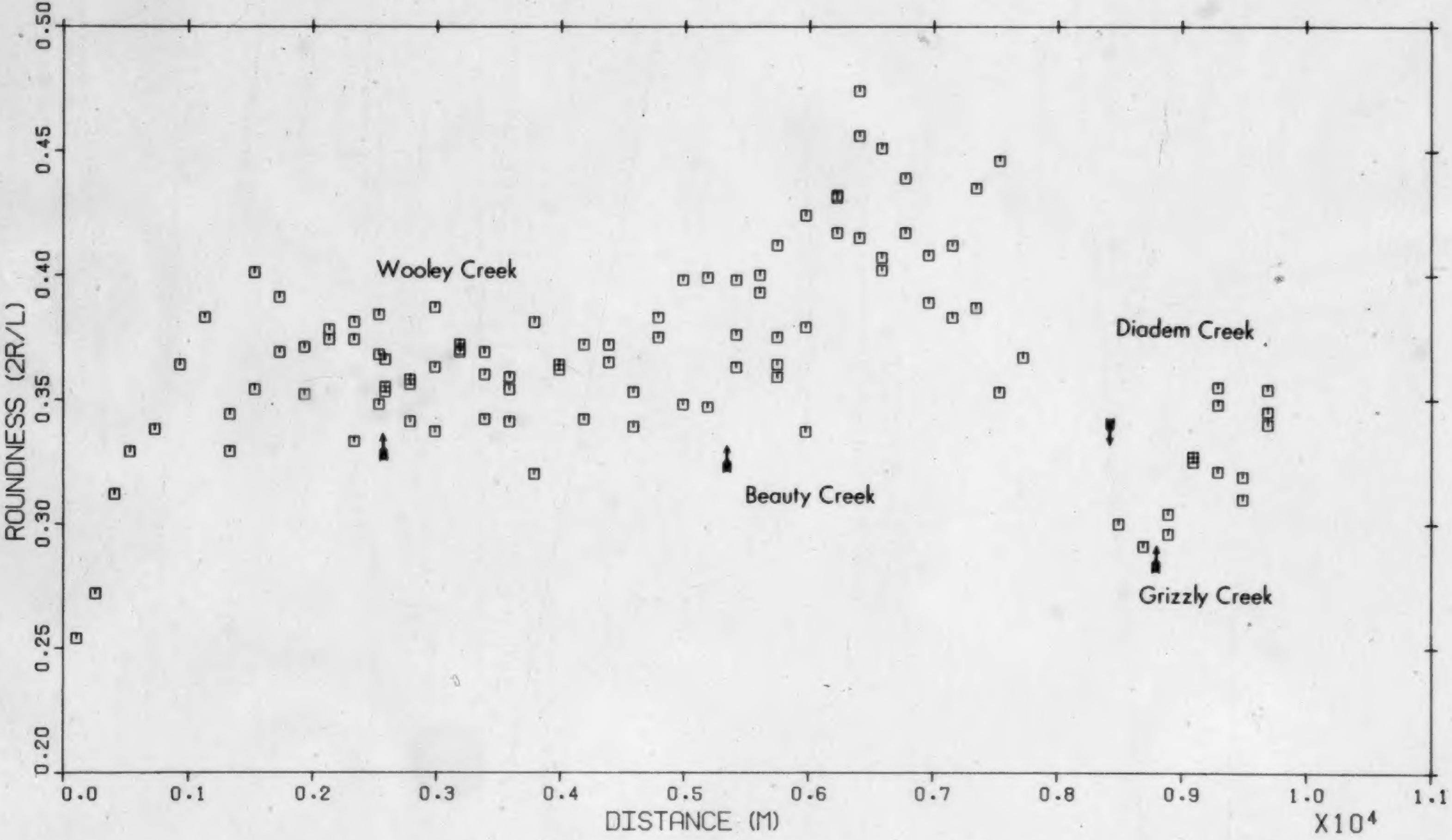


FIG. 4.6 CLAST ROUNDNESS

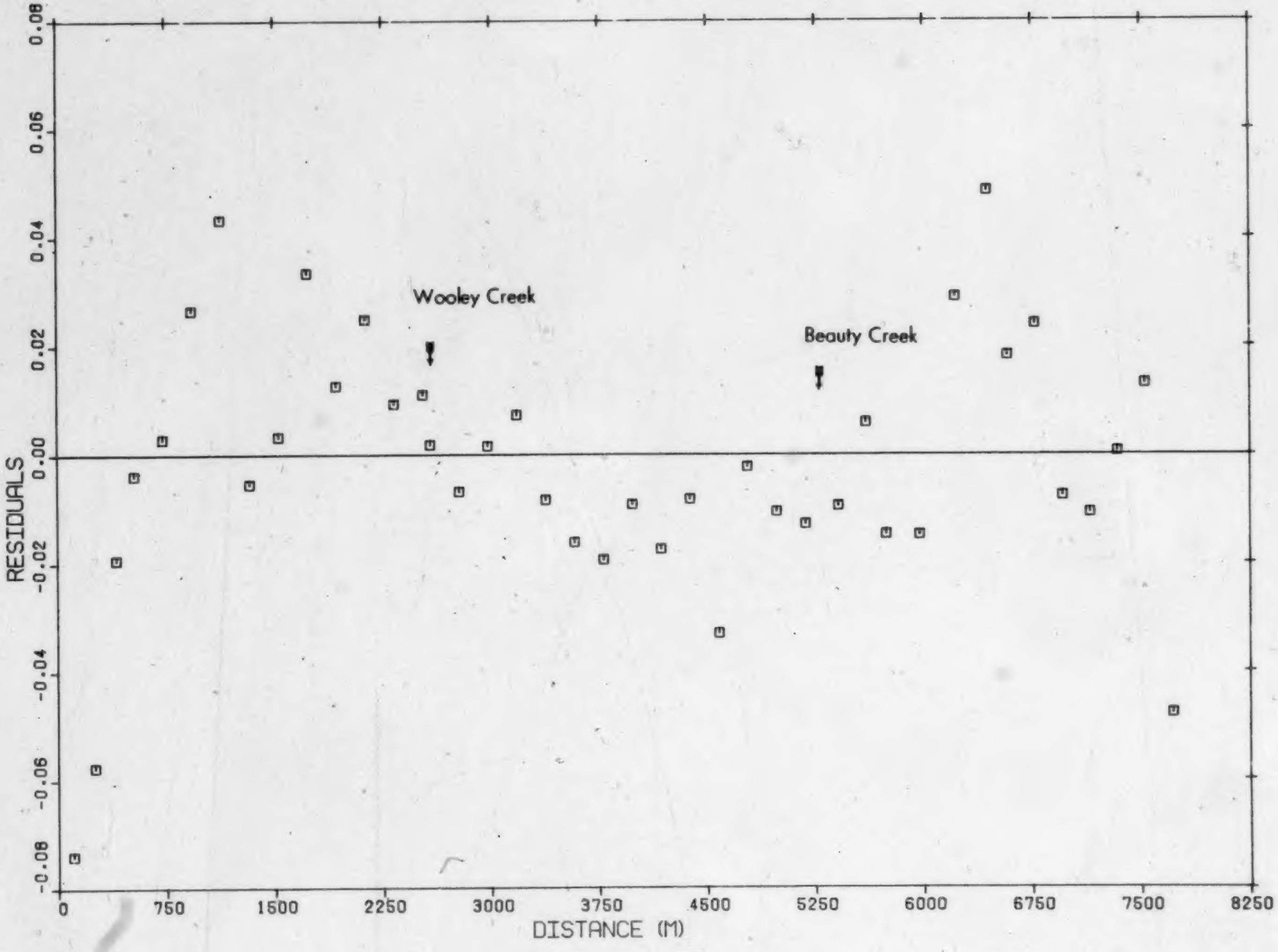


FIG. 4.7 CLAST ROUNDNESS : SMOOTHED RESIDUALS FROM REGRESSION

roundness are best described by two separate terms.

The plot of the residuals also demonstrates an initial increase in roundness (strongly positive residuals) in the distal reach, separate from the general trend between distance and roundness. Subsequently, in the downstream portions of the distal reach there is a rapid decrease in roundness. No particular cause can be ascribed to this variation although it is possibly related to the lithological composition of the samples. There was no indication from either the plot of the smoothed residuals or from the raw data that the tributaries were introducing clasts of markedly different roundness.

Previous workers (Kuenen 1956, Sneed and Folk 1958, and others) have noted that lithology is an important factor controlling roundness. As values of roundness for both the limestone and quartzitic components of the samples were available a paired T-test was carried out comparing the "grand" mean of the limestone roundness values and the "grand" mean of the quartzitic roundness values for each sample. The following null hypothesis was formulated;

> "There is no significant difference between the grand mean roundness for limestone and quartzites."

The significance level was set at 95 percent.

The results of the analysis are shown in Table 4.14, indicating that the grand mean of the roundness values of the limestone is significantly greater than the similar values for the quartzitic component. Hence the null hypothesis was rejected.

The higher values of roundness for the limestones as compared to the quartzitic component of the samples is related to the behaviour of the particles under abrasion, the limestones being less resistant and thus subject to greater wear. True quartzites are more resistant but are prone to fracturing and coarse grained sandstones and conglomerates disintegrate granularly, consequently leading to more angular particles.

Krumbein (1942b) and Kuenen (1956) suggested that size may be an important influence on roundness, with larger pebbles attaining higher values of roundness more rapidly. Krumbein (1942b), however, stated that roundness-distance relationships may be related to differential transport with smaller, rounder pebbles being transported more rapidly. Krumbein (1942b) also suggested that sphericity was an important control on roundness as asymptotic values of roundness were approached. Given that a number of

TABLE 4.14 RESULTS OF THE T-TEST ON QUARTZITIC VERSUS LIMESTONE ROUNDNESS

	No. of Cases	Mean	S.E	Diff	S.E.	Corr	Prob	T	Df	SIG
Quartzitic Roundness	103	0.284	0.005	0.103	0.004	0.63	0.00	-28.81	102	0.00
Limestone Roundness	103	0.388	0.003							

variables have been shown (distance, lithology) or suggested (size, sphericity) to affect roundness, a multiple regression was carried out with roundness as the dependent variable and distance, size, sample percentage limestone and sphericity as the independent variables.

Mark and Church (1977) pointed out that the use of regression analysis may be invalid in a situation where there is experimental error in the determination of the independent variables. The use of regression analysis is appropriate in previous sections, as it was assumed that the explanatory variable, distance, was measured without error. The incorporation of such variables as size into the analysis violates the assumption that the independent variables are error-free. Thus, in this case a functional analysis would be more applicable. However, as no direct comparison is being made between existing theoretical relationships and the relationships determined by the regressions, a regression analysis was used in the present analysis. It must be noted, however, that the relationships described are only approximate, with a strong possibility that the slopes of the relationships may be different from those given by functional analysis.

Mather (1976) outlined an assumption pertaining to multiple regression analysis in addition to those noted in section 4.1;

> The explanatory variables are not perfectly linearly related.

It has been previously shown that size and distance show a strong relationship. Whilst the above assumption is not violated, the effect of one of these variables may be partially masked in multiple regression analysis.

Table 4.15 shows the results of the analysis. The data set was divided at Diadem Creek as in previous analyses. The negative partial correlations between size and roundness indicate that size controls the development of roundness, over and above the relationship between size and distance. It is suggested that distance did not enter the relationships due to its high correlation with size and thus much of the size-roundness relationship is accounted for by distance of travel. However, size contributes some additional explanation, and it is possible, as suggested by Krumbein (1942b), that some form of preferential transport of round, small clasts is taking place. Church (1970), however, pointed out that the roundness measure as used had certain disadvantages, in that artificially low roundness may be ascribed to large clasts if they possess small, but relatively insignificant protruberances. The size-roundness relationship may, therefore, reflect this effect. The partial correlation between the percentage of limestone in a sample and roundness, for the data upstream of Diadem Creek is to be expected given the significantly higher roundness of the limestones as compared to the quartzitic component of the samples.

4.3.2 Clast Flatness

The measure of clast flatness was plotted as a function of distance (Fig 4.8). As with the measures of size and roundness a break occurs in the trend of the data at the Diadem Creek alluvial fan and two regressions were fitted to the data. Table 4.16 shows that only the regression through the data downstream of the Diadem Creek fan is significant. Examination of Figure 4.8 indicates that there are no significant trends in flatness away from the Wooley or Beauty Creek tributaries.

A paired T-test, similar to the T-test used on the roundness measures, was performed to assess the influence of lithology on flatness. The following null hypothesis was formulated;

> "There is no significant difference between the grand means of the values of limestone flatness and and the values of flatness for the quartzitic component of the samples."

The significance level was set at 95 percent. As may be seen from Table 4.17, the quartzitic component is significantly less flat (lower values of the measure indicating flatter clasts), than the limestones. The null hypothesis was therefore rejected. It is suggested that the significant difference in flatness is a function of the original structure of the respective lithologies, the limestones being flatter due to breakage along the bedding planes prior to and during fluvial transport. The quartzites, however, are more prone to breakage across their granular structure, whilst the quartzitic sandstones and conglomerates tend to break around their granular structure.

The flatness measure, as proposed, has a high degree of similarity to Krumbein's (1941) intercept sphericity. Both Sneed and Folk (1958) and Koster (1977) noted complex relationships between shape and size. Given that distance, lithology and possibly size affect flatness, a multiple regression was calculated with flatness as the dependent

TABLE 4.15 RESULTS OF MULTIPLE REGRESSIONS ON ROUNDNESS

Reach	R	R^2	Sig	Partial Corr
Proximal Medial Distal	0.749	0.561	0.000	Size =-0.683 %Lim = 0.267
Inter-Fan	0.844	0.712	0.000	Size =-0.844

TABLE 4.16 REGRESSIONS OF FLATNESS ON DISTANCE DOWNSTREAM

Reach	R	R	Sig	B (Slope)
Proximal Medial Distal	N.S.			
Inter-Fan	0.6876	0.4728	0.000	-0.000074

TABLE 4.17 RESULTS OF THE T-TEST ON QUARTZITIC VERSUS LIMESTONE FLATNESS

	No. of Cases	Mean	S.E	Diff	S.E.	Corr	Prob	T	Df	SIG
Quartzitic Flatness	103	0.577	0.005	0.019	0.004	0.59	0.00	5.16	102	0.00
Limestone Flatness	103	0.557	0.003							

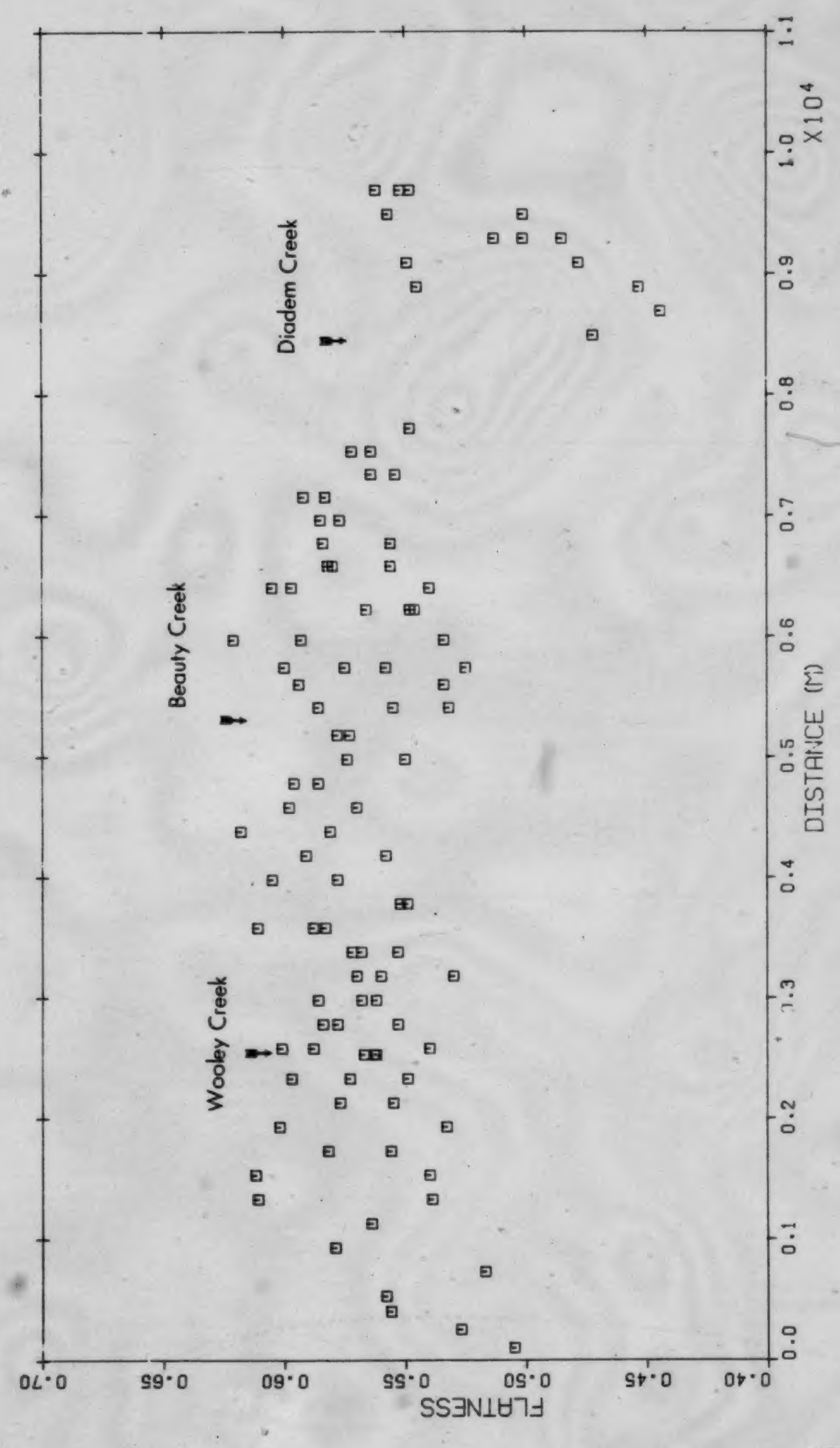


FIG.4.8 CLAST FLATNESS

variable and size, distance and percentage limestone as the independent variables (Table 4.18).

The results indicate that relationships between flatness and the other variables in the river upstream of Diadem Creek are weak and of marginal significance. The relationship downstream of Diadem Creek is strong. This may either result from the short distance shape sorting of material away from the alluvial fan or from the alteration of material due to abrasion. This is not apparent in the river upstream of Diadem Creek as there are no adjacent, large sources of material.

4.3.3 Clast Sphericity

The measure of clast sphericity was plotted as a function of distance (Fig 4.9). As with the closely related measure of flatness, a break in the trend in the data occurred at the Diadem Creek alluvial fan and two separate regressions were fitted to the data (Table 4.19). As with the measure of flatness only the regression below the Diadem Creek tributary was significant. Examination of Fig 4.9 indicates that there are no significant trends in sphericity away from the Wooley or Beauty Creek tributaries.

A paired T-test was performed to assess the influence of lithology on sphericity. The following null hypothesis was formulated;

> "There is no significant difference between the grand mean of the values of limestone sphericity and the values of sphericity for the quartzitic component of the samples."

The significance level was set at 95 percent. As may be seen from Table 4.20 the quartzitic component is significantly more spherical than the limestones and the null hypothesis was rejected. It is suggested that, like the difference in flatness, this is a reflection of the inherent properties of the respective lithologies.

Sneed and Folk (1958) noted a complex relationship between the measure of clast sphericity, used here, and size in the Colorado River, Texas. Given that distance, lithology and possibly size affect sphericity, a multiple regression was performed with flatness as the dependent variable and size, distance and percentage limestone as the independent variables (Table 4.21)

TABLE 4.18 RESULTS OF MULTIPLE REGRESSIONS ON FLATNESS

Reach	R	R^2	Sig	Partial Corr
Proximal Medial Distal	0.337	0.114	0.000	Size =-0.300 Dist =-0.210
Inter-Fan	0.731	0.534	0.000	Size =-0.731

TABLE 4.19 REGRESSIONS OF SPHERICITY ON DISTANCE DOWNSTREAM

Reach	R	R^2	Sig	B (Slope)
Proximal Medial Distal	N.S.			
Inter-Fan	0.6891	0.4748	0.000	-0.000063

TABLE 4.20 RESULTS OF THE T-TEST ON QUARTZITIC VERSUS LIMESTONE SPHERICITY

	No. of Cases	Mean	S.E	Diff	S.E.	Corr	Prob	T	Df	SIG
Quartzitic Sphericity	103	0.695	0.004	0.016	0.003	0.58	0.00	5.32	102	0.00
Limestone Sphericity	103	0.679	0.003							

TABLE 4.21 RESULTS OF MULTIPLE REGRESSIONS ON SPHERICITY

Reach	R	R^2	Sig	Partial Corr
Proximal Medial Distal	0.263	0.069	0.013	Size =-0.263
Inter-Fan	0.734	0.538	0.003	Size =-0.734

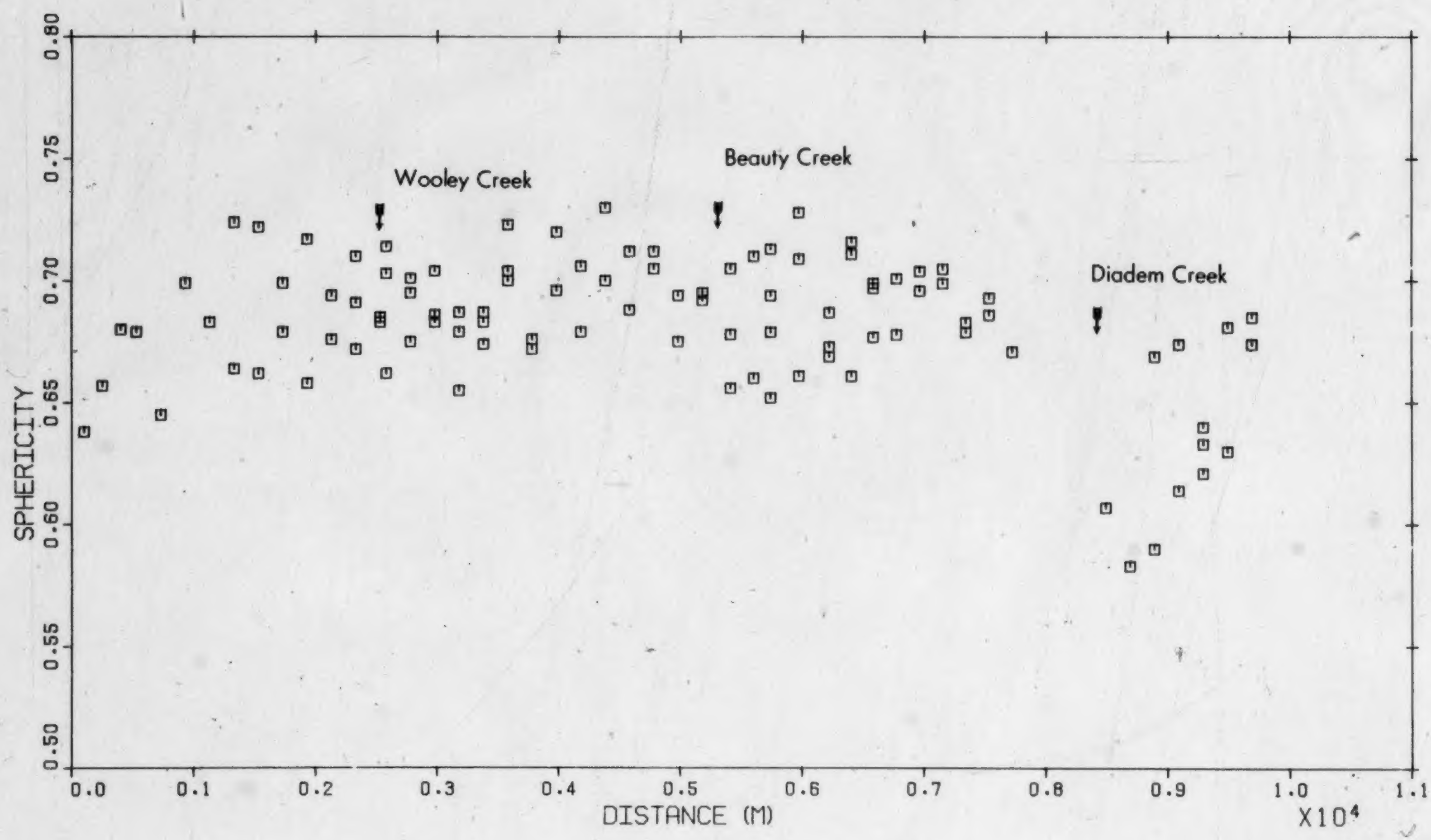


FIG. 4.9 CLAST SPHERICITY

The relationship between size and sphericity is weak in the combined proximal, medial and distal sub-reaches as compared to the relationship downstream from the Diadem Creek fan. This could be related to the existence of a wider range of sizes in the upstream area of the study reach, with, as noted by Sneed and Folk (1958), the larger clasts becoming less spherical downstream and the smaller clasts becoming more spherical downstream. In contrast, the clasts downstream of Diadem Creek may all behave similarly in terms of sphericity development downstream, as they fall within a narrower range of sizes. However, it is more probable, as with the measure of flatness, that the difference in the strength of the two trends, represents the effect of differential sorting or abrasion close to a large source in the inter-fan sub-reach and the absence of such a source in the other sub-reaches.

4.3.4 Zingg Axial Ratios

The percentage of clasts in the respective Zingg (1935) shape classes for each sample were regressed against distance. As with the other measures of clast morphology two regressions were fitted to the data; the data set being divided at the Diadem Creek alluvial fan (Table 4.22). Examination of the graphs of Zingg (1935) category (percent) (Figs 4.10 a to d) against distance indicates that although general relationships in the reach upstream of Diadem Creek are not significant, the shapes may vary with distance within individual sub-reaches. Further regressions were, therefore, calculated for each sub-reach (Table 4.22). The results indicate that there are no consistent relationships between Zingg (1935) shape and distance. Relationships in the proximal and distal sub-reaches are weak, the strongest relationship occurring in the inter-fan sub-reach.

The effect of lithology was assessed using a paired T-test after separating the samples into limestone and quartzitic components. Null hypotheses of the following form were formulated for each of the respective comparisons.

> "There is no significant difference in the grand mean percentage of .... (a certain Zingg (1935) shape class) between the limestone and quartzitic components of the samples."

The significance level was set at 95 percent. As may be seen from Table 4.23, only in

TABLE 4.22 REGRESSIONS OF ZINGG SHAPE CLASSES ON DISTANCE DOWNSTREAM

Reach	Zingg Shape	R	R^2	Sig	B (Slope)
Proximal Medial Distal	Blades	N.S.			
	Rollers	N.S.			
	Spheres	N.S.			
	Discs	N.S.			
Inter-Fan	Blades	N.S.			
	Rollers	0.731	0.534	0.003	0.00994
	Spheres	0.731	0.535	0.003	0.00140
	Discs	0.737	0.544	0.003	-0.01836
Proximal	Blades	N.S.			
	Rollers	0.506	0.256	0.014	-0.00307
	Spheres	0.518	0.268	0.011	0.00500
	Discs	N.S.			
Medial	Blades	N.S.			
	Rollers	N.S.			
	Spheres	N.S.			
	Discs	N.S.			
Distal	Blades	0.356	0.127	0.049	0.00175
	Rollers	0.376	0.141	0.037	0.00272
	Spheres	N.S.			
	Discs	N.S.			

TABLE 4.23 RESULTS OF THE T-TESTS ON THE GRAND MEAN PERCENTAGE OF ZINGG CLAST SHAPES FOR LIMESTONES AND THE QUARTZITIC COMPONENT OF EACH SAMPLE.

	No. of Cases	Mean	S.E	Diff	S.E.	Corr	Prob	T	Df	SIG
Quartzitic Blades	103	9.75	0.708	-2.61	0.712	0.32	0.00	-3.67	102	0.00
Limestone Blades	103	12.37	0.467							
Quartzitic Rollers	103	20.37	0.941	1.747	1.056	0.05	0.65	1.66	102	0.101
Limestone Rollers	103	18.62	0.523							
Quartzitic Spheres	103	34.40	1.294	1.650	1.198	0.43	0.00	1.38	102	0.171
Limestone Spheres	103	32.74	0.829							
Quartzitic Discs	103	35.40	1.212	-0.903	1.320	0.18	0.07	-0.68	102	0.496
Limestone Flatness	103	0.557	0.003							

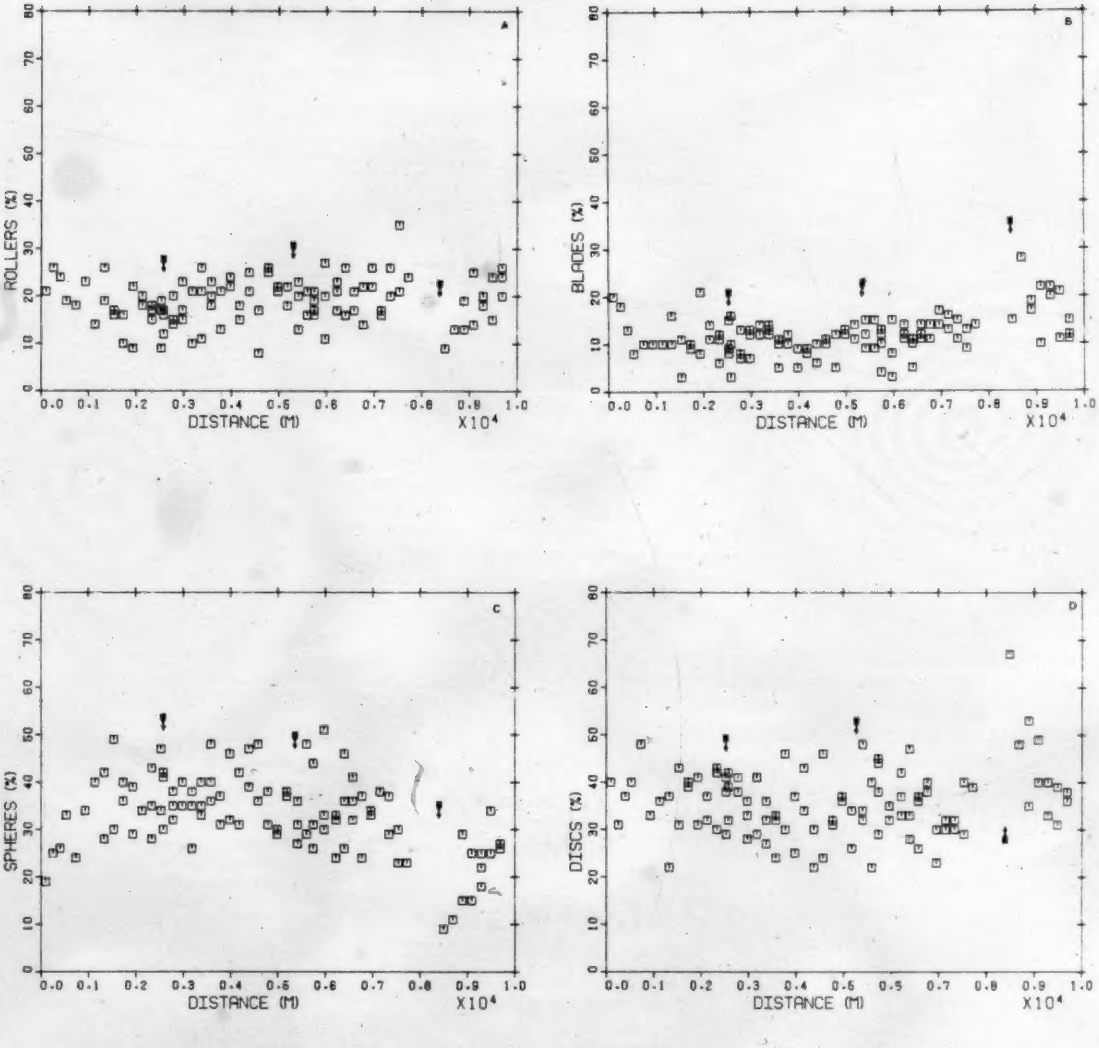


FIG. 4.10 ZINGG AXIAL RATIOS

the case of blades was there a significant difference in the grand mean percentages; there being a greater mean percentage of limestone blades as compared to the quartzitic blades. In all other cases the null hypothesis was accepted.

Given that size was an important influence controlling flatness and sphericity, multiple regressions were fitted to the data with percentage clasts in the respective Zingg (1935) classes as dependent variables and distance, size and percentage limestone as the independent variables. The results of these analyses are shown in Table 4.24. Outside of the inter-fan sub-reach, relationships are generally weak and of low significance, with R^2 values of less than 0.30 indicating that the fitted relationships poorly explain the variation in the data. There is little consistency in the relationships between the Zingg (1935) classes, distance, size and lithology.

4.3.5 Discussion

With the exception of the inter-fan sub-reach there seems to be little significant variation in clast morphology. Whilst there is a possibility that distance-clast form relationships are obscured by complicated size-clast form relationships, as noted by Sneed and Folk (1958) and Koster (1977), it is suggested that shape sorting is not a significant mechanism in the reach upstream of Diadem Creek. However, away from the Diadem Creek tributary, roundness, sphericity, and the percentage of rollers increase with size, and flatness decreases with size. As size and distance are strongly correlated, much of the variation attributed to size may actual represent a shape-distance relationship. The percentage of spheres increases and the percentage of discs decreases with distance. Whilst the increase in roundness indicates that some form of abrasion is occurring it is suggested that there is preferential transport of rounder, more spherical or roller-like clasts. These conclusions differ from those of Unrug (1957) and Bradley *et al.* (1972) who found that spheres and rollers were the least mobile particle shapes. However, Koster (1977) suggested that where clast size-depth ratios were high, as in braided rivers, prolate (roller) forms were more rapidly transported and hence differentially sorted.

The lack of distinct trends in shape sorting in the study reach upstream of Diadem Creek, strongly suggests that shape sorting does not account for the higher rates of size

TABLE 4.24 RESULTS OF MULTIPLE REGRESSIONS ON THE PERCENTAGE CLASTS IN EACH ZINGG SHAPE CLASS

Reach	Zingg	R	R^2	Sig	Partial Corr
Proximal Medial Distal	Blades	N.S.			
	Rollers	0.464	0.216	0.00	%Lim = 0.394 Size =-0.221
	Spheres	0.276	0.076	0.009	%Lim = 0.256
	Discs	0.236	0.055	0.026	Size = 0.236
Inter- Fan	Blades	N.S.			
	Rollers	0.777	0.604	0.001	Size =-0.777
	Spheres	0.731	0.535	0.001	Dist = 0.731
	Discs	0.737	0.535	0.003	Dist =-0.737
Proximal	Blades	0.461	0.213	0.027	Size = 0.461
	Rollers	0.506	0.256	0.014	Dist =-0.506
	Spheres	0.532	0.282	0.009	Size =-0.532
	Discs	N.S.			
Medial	Blades	N.S.			
	Rollers	0.438	0.192	0.010	Size =-0.438
	Spheres	N.S.			
	Discs	N.S.			
Distal	Blades	N.S.			
	Rollers	0.535	0.286	0.002	%Lim =-0.535
	Spheres	N.S.			
	Discs	0.581	0.338	0.003	Size = 0.552 Dist = 0.417

diminution for the quartzitic component as compared to the limestones, although the quartzitic lithologies were markedly less flat and more spherical. Two possibilities may account for the high rates of diminution of the quartzites and the combined quartzitic lithologies. It is possible that the quartzites and quartzitic lithologies are subjected to higher rates of attrition, than those found in other studies, as a result of fracturing. Although greater resistance to wear has been reported for quartzites in flume studies (Kuenen 1956, Bradley 1970), the low roundness values noted in the present study seem to support this hypothesis. The higher diminution coefficients also may result from the input of a relatively coarse quartzite population into the main reach from the tributaries. If such debris forms a lag, a high diminution coefficient for the quartzites would be derived for individual sub-reaches.

The following T-test was devised to test this hypothesis. The four upstream and downstream transects in each sub-reach were placed into two separate groups and the differences between the mean b-axis for the quartzitic and the limestone component of each sample was obtained. The mean of the differences for the upstream group was compared to a similar mean for the downstream group. The following null hypothesis was formulated.

> "There is no significant difference between the mean of the differences between the b-axis size of the quartzitic and limestone components of a sample upstream as compared to downstream in an individual sub-reach"

The significance level was set at 95 percent.

Table 4.25 shows the results of the analysis. In the case of the proximal and distal sub-reaches, the F-test on the sample variances showed that the variances were significantly different at the 95 percent level and hence an approximation to the T-test was calculated using separate variance estimates (Nie *et al*. 1975). The null hypothesis was accepted in all cases except for the distal sub-reach. Thus the higher diminution coefficients for the quartzitic lithologies, with the possible exception of the distal sub-reach, cannot be attributed to the input of a coarse quartzitic lag at each of the tributaries. This is supported by a cursory comparison of the means of the differences for the downstream transects of the proximal sub-reach with the upstream transects of the medial sub-reach and a similar comparison between the medial and distal

TABLE 4.25 RESULTS OF THE T-TESTS ON THE GRAND MEANS OF THE DIFFERENCES IN SIZE BETWEEN THE LIMESTONE AND THE QUARTZITIC COMPONENTS OF SMALL GROUPS OF SAMPLES

Proximal Sub-reach

Group	No. of Cases	Mean	S.E	F	Prob	T*	df	Prob
Upstream	5	22.64	8.989	8.06	0.01	1.50	5	0.194
Downstream	10	8.736	7.080					

* Separate Variance Estimate

Medial Sub-reach

Group	No. of Cases	Mean	S.E	F	Prob	T	df	Prob
Upstream	12	5.939	1.700	1.35	0.711	0.67	18	0.511
Downstream	8	4.232	1.791					

Distal

Groups	No. of Cases	Mean	S.E	F	Prob	T*	df	Prob
Upstream	11	4.459	3.122	7.45	0.014	3.99	13	0.002
Downstream	8	0.370	0.404					

*Separate Variance Estimate

Interfan Sub-reach

Groups	No. of Cases	Mean	S.E	F	Prob	T	df	Prob
Upstream	6	8.775	1.379	1.43	0.69	2.05	9	0.07
Downstream	5	4.196	1.806					

sub-reaches. The mean values in both cases are very similar; if a coarse quartzitic lag was being introduced, there should be a significant difference. Whilst the T-test used for the proximal sub-reach was not significant, the large mean difference value at the upstream end of the sub-reach suggests that a coarse quartzitic component was being introduced and lag deposition of this component may partially account for the higher diminution coefficients in the proximal sub-reach.

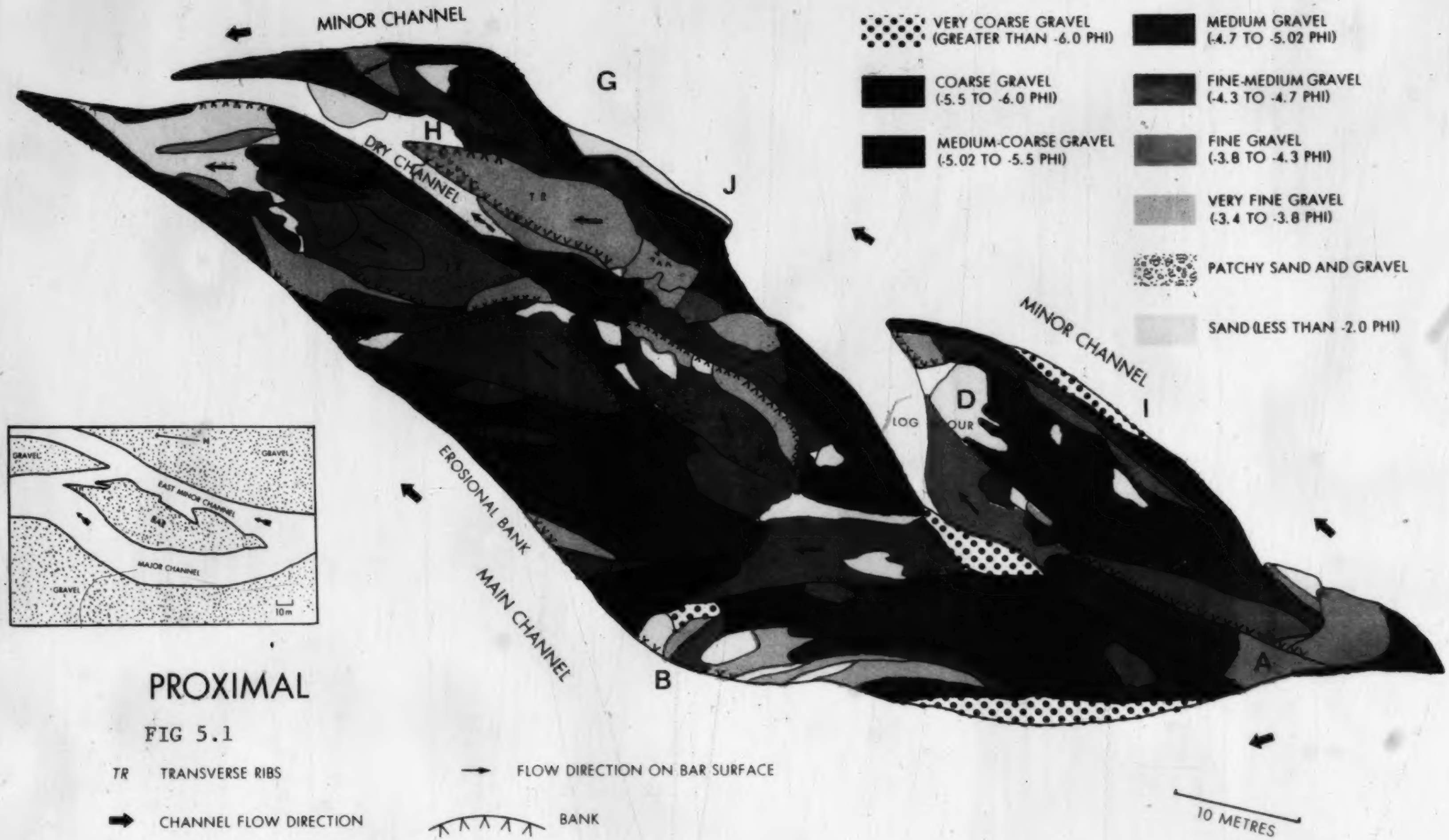
5. SURFICIAL SEDIMENT VARIATIONS ON COMPLEX BRAID BARS

5.1 Bar Location

Three braid bars were selected as being representative of gravel depositional forms in the proximal, medial, and distal sub-reaches. The proximal sub-reach braid bar (Fig.5.1) was located adjacent to the main channel approximately 500 m from the point of emergence of the Sunwapta River onto the Beauty Creek flats. The main channel flowed to the west of the braid bar with the east bank of the bar being defined by a minor channel system (see inset Fig.5.1). The downstream limits of the bar were poorly defined by a small channel. Downstream of the bar was a large depositional area, the bar itself being the upstream expression of an extensive gravel flat. The development of the bar was not observed, and it remained largely stable throughout the period of mapping, with only minor erosion occurring along portions of the west bank. Subsequent to the period of mapping the main channel shifted laterally, westward, with in-channel deposition occurring along the base of the west bank of the bar.

The medial sub-reach braid bar (Figs 5.2 and 5.3) was a small medial form situated in a secondary channel system, approximately 1200 m downstream of the Wooley Creek alluvial fan. The secondary channel system was observed to develop initially through the re-occupation of former channels, with only limited modification by erosion and deposition. However, it is suggested that the bar was formed during this re-occupation. Mapping was accomplished during a period of diminished discharge in the channel system; little alteration occurred over a period of four days. However, as a result of greatly increased discharge in the system, extensive modification of the braid bar and its environs took place after the mapping was completed, and only small remnants of the bar were discernible seven days later.

The gravel areas mapped (Fig 5.2) represent a complex juxtaposition of both erosional and depositional features. The braid bar, located centrally on the map, and a point bar form, located slightly downstream at A., are both largely depositional forms. The surrounding areas are mainly remnants of former, partly stablised, gravel flats. For instance, the partially vegetated, sinuous, gravel area to the east of the braid bar, area B, was defined by two parallel minor channels at different elevations, and was undergoing


MINOR CHANNEL
G
H
DRY CHANNEL
TR
J
MINOR CHANNEL
D
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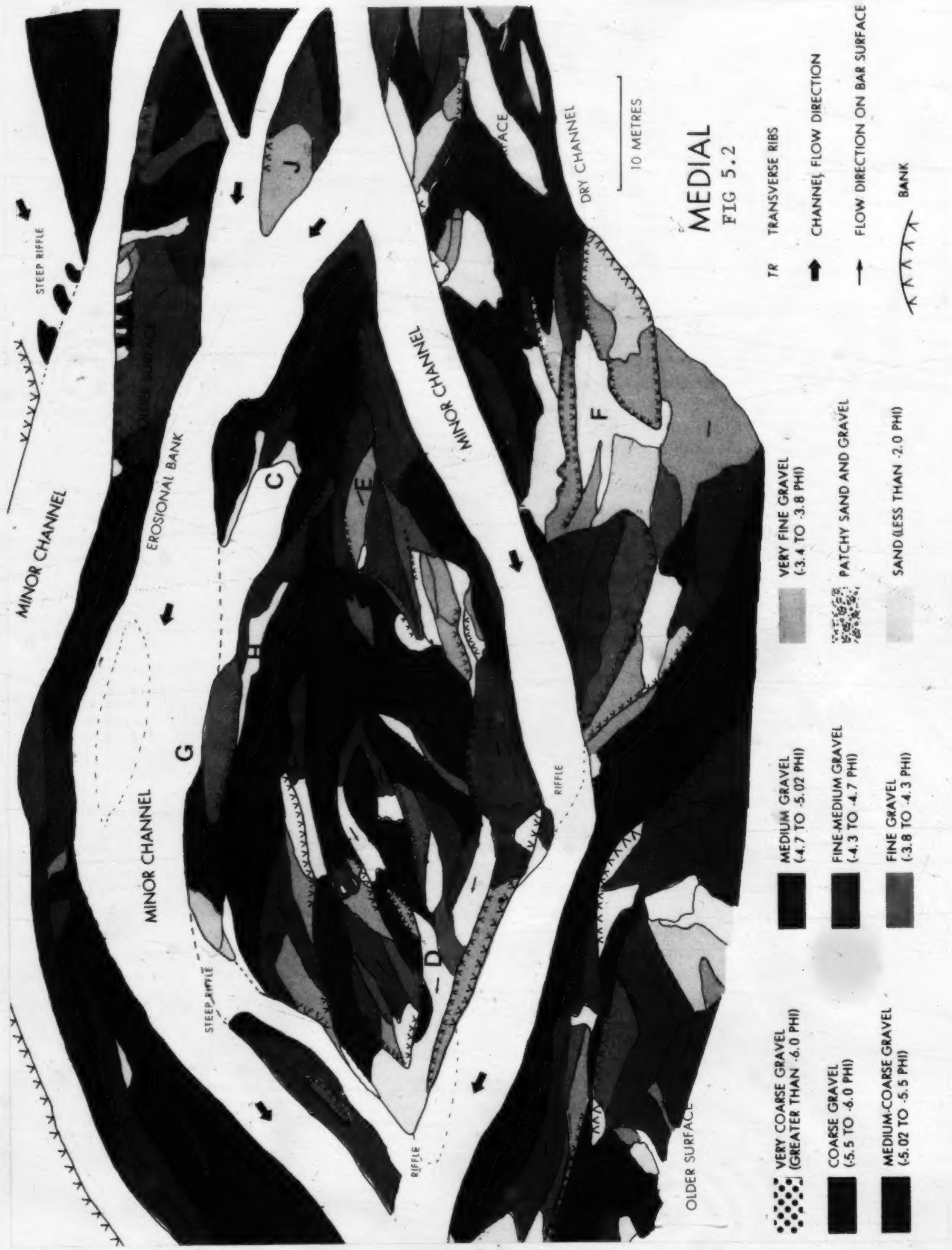
OUR
I
EROSIONAL BANK
MAIN CHANNEL
B
A
VERY COARSE GRAVEL (GREATER THAN -6.0 PHI)
COARSE GRAVEL (-5.5 TO -6.0 PHI)
MEDIUM-COARSE GRAVEL (-5.02 TO -5.5 PHI)
MEDIUM GRAVEL (-4.7 TO -5.02 PHI)
FINE-MEDIUM GRAVEL (-4.3 TO -4.7 PHI)
FINE GRAVEL (-3.8 TO -4.3 PHI)
VERY FINE GRAVEL (-3.4 TO -3.8 PHI)
PATCHY SAND AND GRAVEL
SAND (LESS THAN -2.0 PHI)
10 METRES
GRAVEL
N
GRAVEL
EAST MINOR CHANNEL
BAR
MAJOR CHANNEL
GRAVEL
10m
TR TRANSVERSE RIBS
FLOW DIRECTION ON BAR SURFACE
CHANNEL FLOW DIRECTION
BANK

PROXIMAL

FIG 5.1


MINOR CHANNEL
STEEP RIFFLE
OLDER SURFACE
EROSIONAL BANK
MINOR CHANNEL
MINOR CHANNEL
STEEP RIFFLE
RIFFLE
RIFFLE
OLDER SURFACE
DRY CHANNEL
ACE
C
D
E
F
G
H
J
10 METRES
VERY COARSE GRAVEL (GREATER THAN -6.0 PHI)
COARSE GRAVEL (-5.5 TO -6.0 PHI)
MEDIUM-COARSE GRAVEL (-5.02 TO -5.5 PHI)
MEDIUM GRAVEL (-4.7 TO -5.02 PHI)
FINE-MEDIUM GRAVEL (-4.3 TO -4.7 PHI)
FINE GRAVEL (-3.8 TO -4.3 PHI)
VERY FINE GRAVEL (-3.4 TO -3.8 PHI)
PATCHY SAND AND GRAVEL
SAND (LESS THAN -2.0 PHI)
TR TRANSVERSE RIBS
CHANNEL, FLOW DIRECTION
FLOW DIRECTION ON BAR SURFACE
BANK

MEDIAL

FIG 5.2

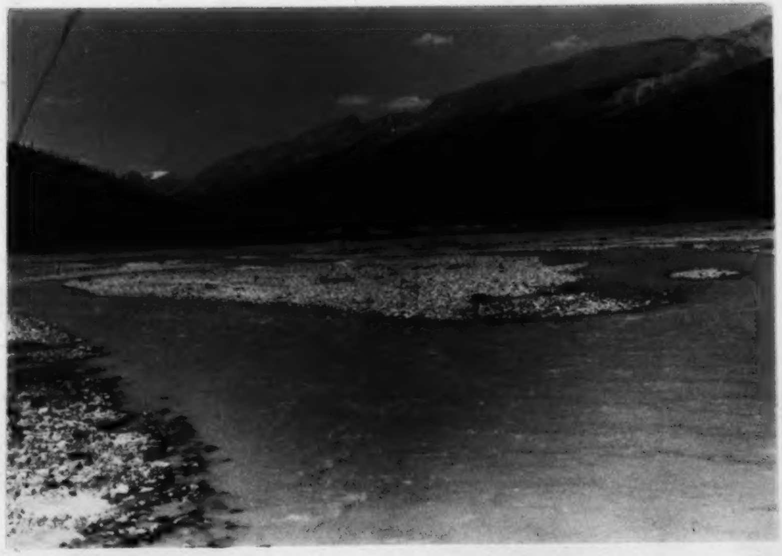


Figure 5.3 Medial Sub-Reach Braid Bar, Photographed from Upstream

erosion during the period of observation.

The distal sub-reach braid bar (Fig 5.4) was a medial form orientated transversely to the reach, but obliquely to the flow in the main channel. The bar was flanked on its south side by the main channel, and to its north side by a minor channel. The downstream margin was delimited by a small channel of limited significance and the bar, therefore, represents the upstream extension of a broad depositional area (see inset Fig 5.4). The evolution of the bar and surrounding forms was not observed and high discharges made impossible a return to the area after the mapping was completed.

5.2 Morphological Features

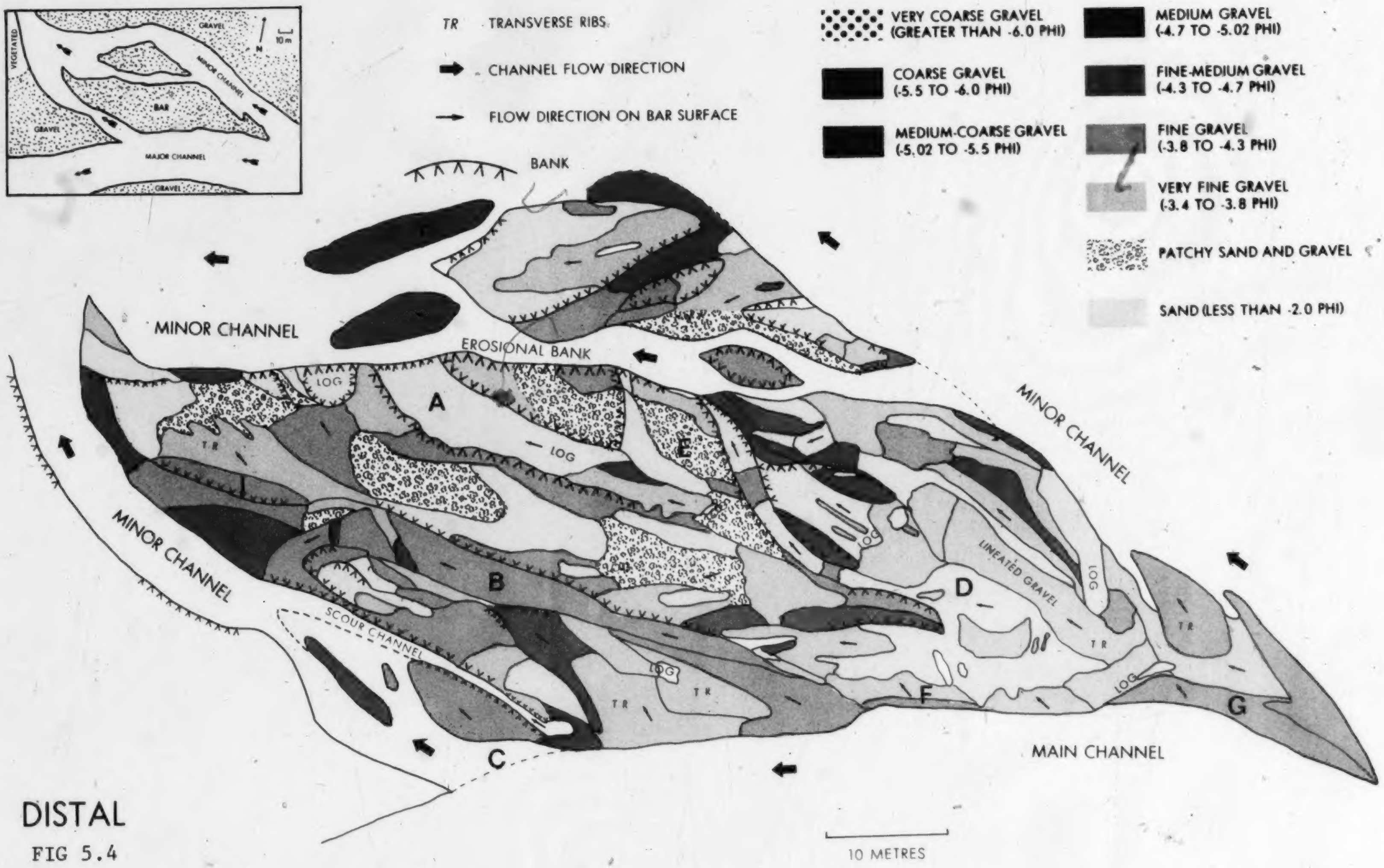
As may be noted from Figs 5.1, 5.2, 5.4, the surface morphology of each braid bar is apparently unique. However the three bars do have a number of features in common.

5.2.1 Minor Channels

A distinction may be made between channels which formed in conjunction with the deposition of the main body of the bar (Type A), and channels which formed as a result of the modification of the bar surface (Type B). It may be suggested that the type A channels are relict forms of the same magnitude and origin as the channels which delimit the braid bar. They were observed only to carry flow at high stage.

5.2.1.1 Type A channels

Type A channels occur on all three bar surfaces, (Location A, Figs 5.1 and 5.5; Location C, Fig 5.2; Location A, Figs 5.4 and 5.6). Where unmodified, these channels typically have at least one steep bank and delimit depositional areas. The channels vary in size, but range between 2-4 m in width. They may occur in any position on the bar surface, but are located predominantly on the upstream portion of the bar, often extending away from an upstream channel margin, and show an orientation parallel or sub-parallel to the surrounding channels. Gravel sizes on the beds of the channels are usually coarse, although frequently the former bed is buried by sand deposited at low flow stages. Where the form of the channel has been extensively modified by later


VEGETATED
GRAVEL
N
10 m
MINOR CHANNEL
BAR
GRAVEL
MAJOR CHANNEL
GRAVEL
TR TRANSVERSE RIBS
CHANNEL FLOW DIRECTION
FLOW DIRECTION ON BAR SURFACE
BANK
VERY COARSE GRAVEL (GREATER THAN -6.0 PHI)
COARSE GRAVEL (-5.5 TO -6.0 PHI)
MEDIUM-COARSE GRAVEL (-5.02 TO -5.5 PHI)
MEDIUM GRAVEL (-4.7 TO -5.02 PHI)
FINE-MEDIUM GRAVEL (-4.3 TO -4.7 PHI)
FINE GRAVEL (-3.8 TO -4.3 PHI)
VERY FINE GRAVEL (-3.4 TO -3.8 PHI)
PATCHY SAND AND GRAVEL
SAND (LESS THAN -2.0 PHI)
MINOR CHANNEL
EROSIONAL BANK
LOG
A
LOG
E
MINOR CHANNEL
TR
MINOR CHANNEL
B
SCOUR CHANNEL
LOG
TR
TR
C
D
LINEATED GRAVEL
LOG
TR
TR
F
LOG
G
MAIN CHANNEL
10 METRES

DISTAL

FIG 5.4

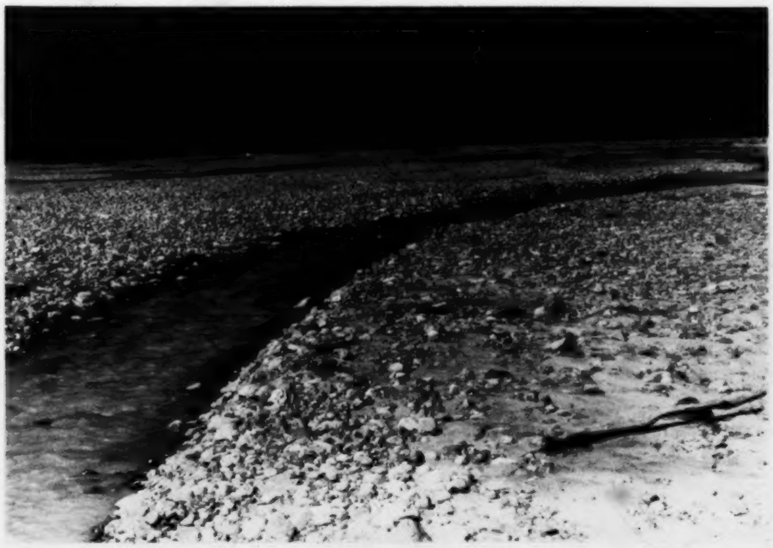


Figure 5.5 Type A channel, Proximal Sub-Reach Braid Bar (View downstream).
At low stage the channel contained no flow.

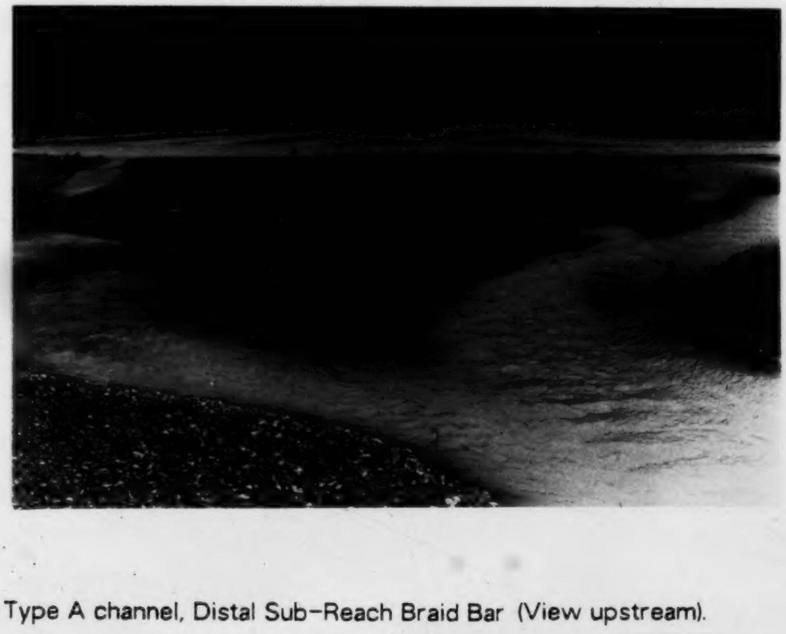


Figure 5.6 Type A channel, Distal Sub-Reach Braid Bar (View upstream).
Type A channels to left and centre of picture. The overbank fining trend occurs in the vicinity of the log in the centre of the photograph.

flows, for instance at location B (Fig 5.1), the presence of coarse gravel is the only indication of a former channel.

The channels represent former minor channels which have been abandoned as a result of flow avulsion. Abandonment is caused by deposition at the upstream end, which results in the downstream portions of the channel being preserved, with little modification by waning flow. Such deposition occurred at Location B (Fig 5.4).

5.2.1.2 Type B Channels

Type B channels are also discernable on all three of the bar surfaces, for instance at location C, (Fig 5.1); locations D and E, (Fig 5.2) and location C, (Fig 5.4). It is suggested that these channels are similar to the minor, scour channels noted by Krigstrom (1962), Ore (1964), Williams and Rust (1969), Rust (1972), Bluck (1974, 1979), Gustavson (1974), and Boothroyd and Ashley (1975). These channels are generally narrower than the type A channels (width less than 2 m), they occur in multiples over a limited area of the bar and tend to show a more variable trend in relation to the local flow direction around the bar than do the type A channels. Type B channels are typically located towards the downstream portions of bars, although channel systems may extend upstream towards bar heads. As Williams and Rust (1969) noted, the channels may be discordant or erosional relative to each other, and may be of limited extent, disappearing gradually either upstream or downstream, or coalescing. The orientation of the channels is often unpredictable, although they may diverge upstream and converge downstream.

5.2.2 Minor Scours and Chutes

Minor scours occur extensively over the bar surfaces, frequently in association with driftwood, lying on the bar surface, which forms an obstruction around which flow is forced to diverge. The size and orientation of the scours varies, but they generally range in length between 30 and 100 cm. They are usually deepest at their upstream end, in the vicinity of the object inducing the scour, and show an ellipsoidal outline. Depths of scour are in the range of 10-20cm. It is suggested that such features are similar to the ellipsoidal scours of Williams and Rust (1969).

Chute channels are similar features, eroded into the sides of steep banks. These extend headwards from the base of the bank, widening as the top of the bank is approached. The scale of such structures is variable, but they may reach 2m in length and 50cm in width.

Examples of both scours and chute channels occurred at location D (Figs 5.1 and 5.7). It is suggested that these features develop as a result of modification of the bar surface on waning flow or by later, high flows.

5.2.3 Gravel and Sand Sheets

A major component of all the bar surfaces are extensive sheets of sand and gravel. Figures 5.8 and 5.9 show examples of gravel sheets at locations E (Fig 5.8) and F (Fig 5.9), Fig 5.1. The gravel sheets, when unmodified, are extensive and show a relatively uniform grain size. The margins of each sheet are often poorly defined and sheets grade almost imperceptably into adjacent sheets. The sheets tend to be coarser and more extensive at the upstream ends of bars. When modified the gravel sheets may exhibit transverse ribs, lineations, and superimposed areas of sand and fine gravel. It is suggested that the relatively uniform gravel sheets are formed during the deposition of the primary bar structure and are subsequently modified. The planar nature of the sheets implies that these areas are the remnants of the diffuse gravel sheets, described by Hein and Walker (1977), which represent the initial form of in-channel deposition. Bar formation will be discussed in greater detail below.

Sand occurs in various locations on bars, but sand sheets are found predominantly on bar tails, for example at location F, (Fig 5.1) and location D, (Fig 5.2.) As the general grain size diminishes in the reach, the areas of sand become more extensive on the bar surfaces and sand sheets occur widely on the distal sub-reach braid bars (location D, Fig 5.4). Where gravel sizes are fine, sand and gravel may be simultaneously deposited. Such deposits may be distinguished from those in which sand is deposited over gravel as the sand forms a matrix for the gravel. This occurs, for example, at location E, (Fig 5.4). Sand also tends to infill features on the bar surface, for example minor channels (location A, Fig 5.4) and areas between transverse ribs (Fig 5.5, foreground). It is suggested that sand deposits on a bar surface are largely a result of deposition by waning or later, lower flows than those which transported gravel to the bar top.

Figure 5.7 Minor Chutes and Scours, Proximal Sub-Reach Braid Bar (View upstream). The chutes and scours occur beneath and to the right of the large log.

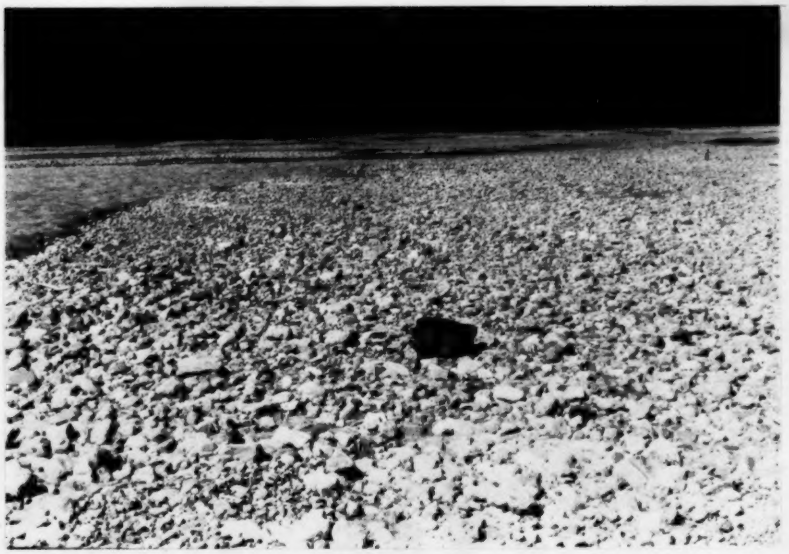


Figure 5.8 Coarse Gravel Sheet, Proximal Sub-Reach Braid Bar
(View downstream. Bag for scale).

Figure 5.9 Fine Gravel Sheet, Proximal Sub-Reach Braid Bar
(View downstream. Bag for scale).

5.2.4 Lobes on the Bar Surfaces

Lobes on the bar surfaces occur predominantly at the downstream ends of bars, for instance, at location H, (Fig 5.1), and location D, (Fig 5.2). They may be variable in form, but are typically linguoid, with a convex downstream avalanche face at the downstream end. The avalanche face is generally between 20 and 30 cm high. The lobes tend to occur downstream of a type B channel system, or where flow from the surrounding channels spreads over the bar surface. The lobes typically show a downflow fining. It is suggested that such lobes are formed by flows which cross the bar surface after the deposition of the main structure, either during waning flow or during later high flow stages and transport a limited amount of sediment; some of which may be derived by scour of type B channels.

5.2.5 Levées

Levées occur along the margins of active channels, for instance at location F and G (Figs 5.10 and 5.11), Fig 5.3. They are typically 1-2 m wide and are generally 1-2 clasts high. The levée deposits fine rapidly away from the channel (Figs 5.10 and 5.11). Levées probably develop when flow overtops the banks of a channel and fine gravel is deposited in the area of lower competence immediately adjacent to it. Such forms, therefore, represent a modification of a bar surface.

5.2.6 Transverse Ribs and Lineated Gravel

Transverse ribs occur widely on the bar surfaces in a range of gravel sizes (Figs 5.12 and 5.13), most frequently in the areas adjacent to active channels. The downflow orientation of the ribs tends to be oblique to the direction of the flow in adjacent channels. The ribs are generally 1-2 clasts high and 2-4 clasts wide, spaced at distances of 15-30cm. Shaw and Kellerhals (1977) and Koster (1979) proposed that similar forms were antidune bedforms, the gravel sizes and the spacing of the ribs being related to the depth and velocity of the flows causing their formation. Thus clast size and rib spacing in the exposed ribs seem to be related. The areas between the clasts are frequently infilled with sand and where this sand covering is extensive, the ribs may be partially buried. Bluck (1979) suggested that transverse ribs were emplaced at a lower flow stage than

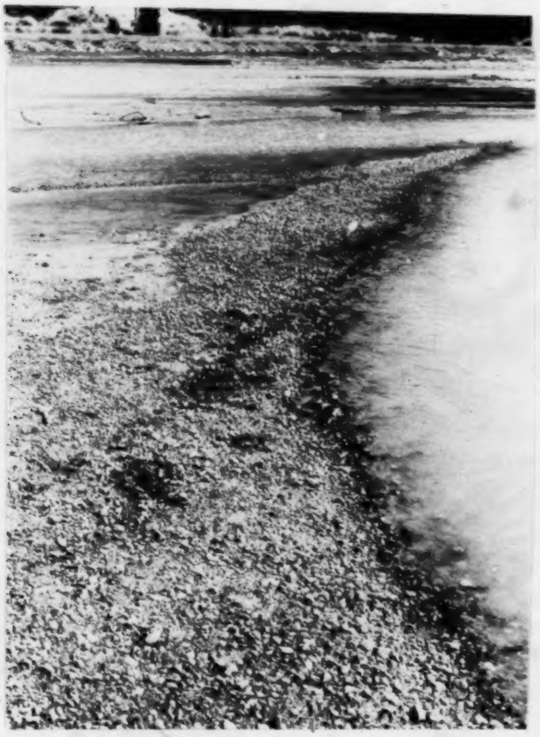


Figure 5.10 Levée. Distal Sub-Reach Braid Bar (View upstream).

Figure 5.11 Levée. Distal Sub-Reach Braid Bar (View downstream).
Levée extends for approximately 2m away from channel.

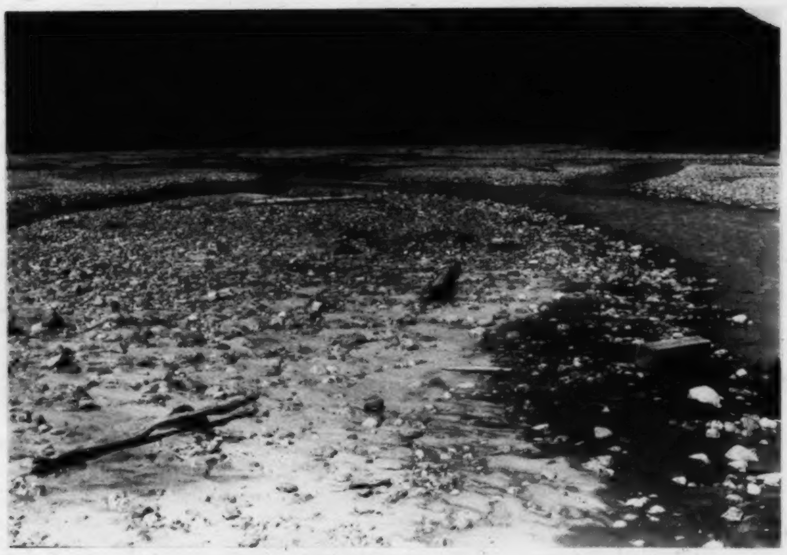


Figure 5.12 Transverse Ribs, Proximal Sub-Reach Braid Bar (View downstream).
The ribs here are poorly developed and are largely covered by a sand drape.

Figure 5.13 Transverse Ribs, Medial Sub-Reach Braid Bar (View downstream).

the main structure of the bar. Morphological evidence on the mapped areas strongly supports this hypothesis; three locations are of note. At location C, (Fig 5.2) minor channels graded downstream into an area of transverse ribs. The co-existence of the minor channels and the transverse ribs seems to suggest that these features developed contemporaneously. At location D, (Figs 5.1 and 5.7) the transverse ribs on an elevated area, (area G, Fig 5.13) grade towards and into the chute channels cut into the steep bank. The occurrence of transverse ribs in the chute channel at location E, (Fig 5.1) indicates that the ribs formed after the erosion of the chute channels, and, therefore, subsquent to the emplacement of the main bar structure. Fig 5.14 (Location E, Fig 5.2) shows a juxtaposition of coarse transverse ribs, lobes of fine gravel and minor, type B channels downstream of a type A channel. The adjacent lobes and channels occur downstream of the transverse ribs. The ribs grade into the minor channels and the lobes and it is suggested that the fine gravels in these lobes represents material winnowed from the area in which the ribs occur, during their development. The area of ribs grades into the lobes, indicating that the two features were formed contemporaneously. It is proposed that inter-rib deposits of sand are emplaced after the transverse ribs as the sand frequently obscures the clasts in the ribs.

Lineated gravel or longitudinal ribs occur only in fine gravel, frequently downstream of large protruding clasts or logs. They comprise multiple, parallel bands of gravel one clast high and 1-2 clasts wide. At location D, (Fig 5.4) such lineations occurred for a distance of 10 m downstream of a log resting on the bar surface. The juxtaposition of the lineations with an upstream obstacle indicates that they were formed at waning or during a later high flow after the emplacement of the body of the bar, possibly by tubular vortices developing around the upstream obstruction (Rust 1972).

5.2.7 Ripples, Minor Scours and Current Crescents

Ripples and minor scours, occurred widely in sand areas on the bar surfaces. It was noted, however, that ripples tend to be concentrated where the former channels were infilled by sand. Current crescents tended to be associated with sand deposited over coarse clasts.

5.2.8 In-Channel Forms Surrounding the Bars

Depositional forms occurred in the minor channels surrounding the bars and frequently they were attached to the bar structures. Predominantly these forms occurred as small lobes for instance at location F, Figs 5.2 and 5.15) and locations C and H, (Fig 5.4). The lobes were up to 10-12 m in length and 3-5 m wide. The upstream margins tended to be submerged and the downstream margins consisted of a poorly defined avalanche face. At certain locations such lobes overlapped, for instance at location F, (Fig 5.2). the lobes occurred in areas of shallow, diverging flow where a channel widened (Location F, Fig 5.2). They were also evident where channel avulsion had taken place. (Location C, Fig 5.4). The lobes represent small unit bars similar in form to those described by Smith N.D. (1974) and Hein and Walker (1977), and are the result of the deposition of gravel in shallow areas of a channel where flow competence is reduced.

It is tentatively suggested that an alternative form of in-channel deposition is evident at location A, (Figs 5.2 and 5.16). The form shown is morphologically similar to point bars described by McGowen and Garner (1970), Smith N.D. (1974), and Jackson (1978), and has a convex-upward profile. The bar developed along the steep inner bank, at the foot of which runs a partially infilled chute channel of a large radius channel bend. Grain size diminishes rapidly away from the channel and downstream. It may be suggested that this form is a point bar which developed as result of migration of the minor channel. The distinct fining trends over the bar surface possibly indicate that the channel was sufficiently deep for transverse helicoidal flows to develop, although trends in the finer gravel sizes may have resulted from later overbank flows.

5.2.9 Partially Vegetated, Raised Areas

Partially vegetated, raised areas only occurred on the distal sub-reach braid bar, but their existence has important implications for braid bar development. These areas, for instance area E, (Figs 5.4 and 5.17), stood approximately 20-40cm above the rest of the bar surface and were frequently bounded by type A channels. The surfaces were covered by fine gravel, sand and patchy areas of both sand and gravel. Often there was limited vegetation cover. The existence of these areas in conjunction with lower,

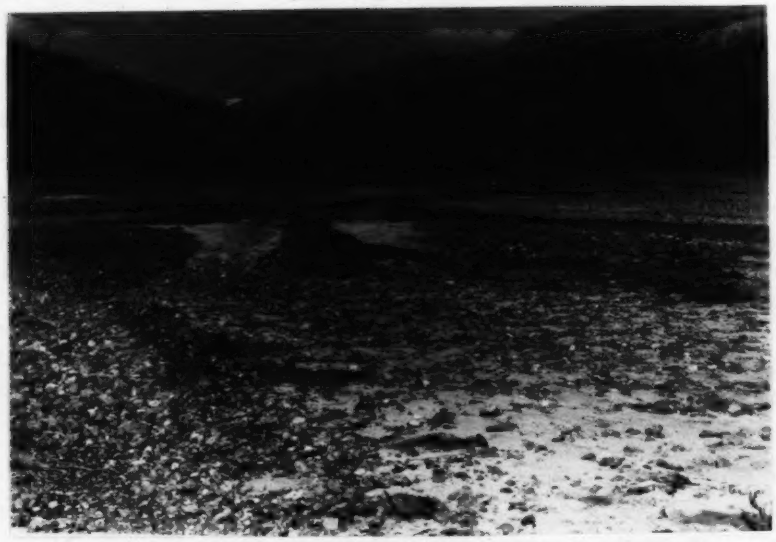


Figure 5.14 Transverse Ribs and Lobes, Medial Sub-reach Braid Bar (View downstream).

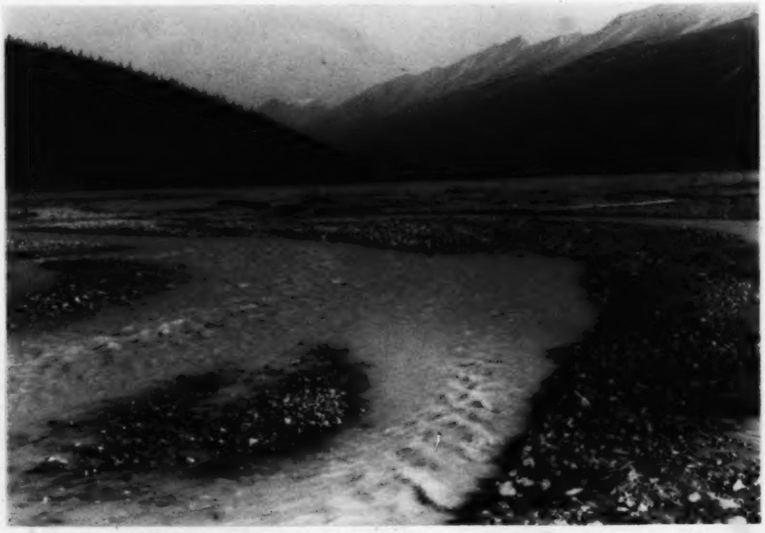


Figure 5.15 In-Channel Lobes, Medial Sub-Reach Braid Bar (View downstream).
Main body of the bar is to the left.

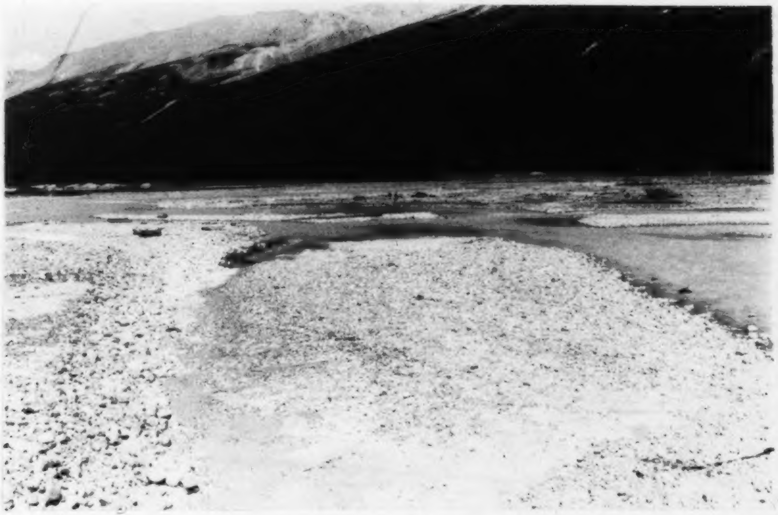


Figure 5.16 Point Bar Adjacent to Medial Sub-reach Braid Bar (View downstream) The area of coarse gravel to the left of the picture is at the base of a steep bank. The bank top is older and partly vegetated.

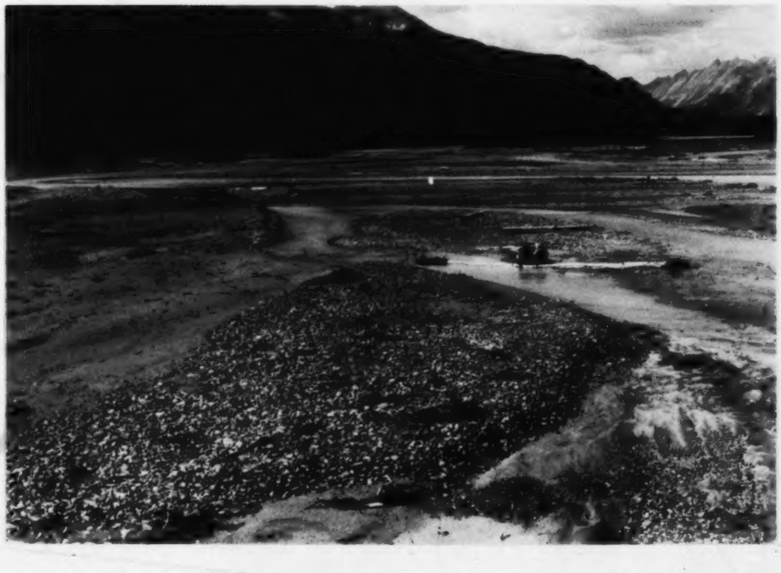


Figure 5.17 Elevated Area, Distal Sub-Reach Braid Bar (View downstream).

unvegetated areas strongly indicates that braid bar development may be the result of deposition in widely separated episodes, and not just as a result of sequential deposition over a short period of time.

5.3 Local Sediment Size Sorting

5.3.1 Trends Away From Channels

5.3.1.1 Point Bar Forms

The point bar at location A, (Figs 5.2 and 5.16) shows a distinct fining trend away from the active channel and downstream along the bar. The gravel fines from coarse gravel (−5.6 phi) to fine gravel (−4.0 phi) over a distance of 8−10 m.[1] A similar fining trend occurs at location I, Fig 5.1 where gravel sizes fine from very coarse gravel (−6.2 phi) to fine-medium gravel (−4.4 phi) over a distance of 3−5 m.

Although McGowen and Garner (1970) noted that vertical fining trends, and by implication, lateral fining trends, did not occur in the coarse grained point bars that they examined, it is proposed that the sorting trends exhibited here developed in conjunction with the formation of the bar. The occurrence of coarse gravel, of similar size to the channel bed gravel along the channel margins, and the existence of a relatively steep channel margin seems to preclude the formation of the fining trend by overbank deposition (discussed below). However fining trends in the finer gravel sizes may have partially resulted from this mechanism. It is suggested that such fining trends develop as a result of the differential transport of sediment by transverse helicoidal flows. These occur in asymmetric channels at a channel bend and at high flows extend over the surface of a point bar.

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[1] The phi values given here represent the median values of the gravel size classes ascribed during the mapping of the bars. The sizes were obtained from the size-visual category cross-comparison (Fig 3.1). The terms very "coarse gravel" and "fine gravel", are the descriptive terms given to each of the size categories.

5.3.1.2 Levées

Levées, like point bar forms, show a rapid fining trend away from a channel. They may be distinguished from the sorting patterns developed in point bar formation, as the sediment sizes at the immediate channel margin are considerably finer than the in-channel sediments. Examples of such fining trends occur at location E, (Figs 5.4 and 5.10), where gravel fines from fine-medium gravel (-4.4 phi) to sand over a distance of 3 m, and at location F, (Figs 5.4 and 5.11), where the fining trend occurs over a distance of 8 m from a former channel margin. The fining is produced in such circumstances as a result of overbank flow, gravel and then sand being deposited progressively as competence declines away from the channel margin.

5.3.1.3 Overflow and Lobe Areas

Sorting trends also occur where there has been extensive flow over the bar surface from the active channel or downstream of type B channel systems. Such trends develop, in general, over areas much larger than those occupied by levées and, unlike trends developed on point bars, tend to have an upstream origin in an area of limited scour, or along low channel banks. Frequently, the downstream margin of deposits with a fining trend is an avalanche face or lobe. A number of examples of this are evident on the braid bars mapped, for instance at locations J and K , (Fig 5.1) and locations F (Fig 5.12), H (Fig 5.18) and I, (Fig 5.2). Where trends occur away from an active or type A channel, the following sequence is often discernible;

1) an area of coarse gravel (-5.5 phi) at the channel margin, grading into;

2) an area of transverse ribs, in which the constituent gravel fines downstream, grading into;

3) an area of fine gravel (-4.2 phi), often in lobe form, with continued fining downstream towards the avalanche face.

Such trends may extend over considerable distances, up to 20 m, as at location J, (Fig 5.1) and location H, (Fig 5.2).

Away from type B channel systems, the fining trend usually occurs across a lobe form which originates at the downstream end of the channel or along the channel margin, as at location K, (Fig 5.1) and location I, (Fig 5.2).

Figure 5.18 Overflow Fining Trend, Medial Sub-Reach Braid Bar (View downstream). The fining trend is best developed to the right of the picture and it extends away from the active channel margin.

It is proposed that such fining trends develop as a result of flows over the bar surface, after deposition of the bar itself. These transport sediment and form lobes. The competency of the transporting flows diminish with distance from the active, or type B, channels due to divergence and declining velocities as a result of a reduced flow surface slope.

5.3.2 Fining Trends on Lobes Within Channels

Downflow fining trends were noted on lobes deposited in channels, for instance at locations F (Fig 5.15) and J, (Fig 5.2). The most distinct fining occurred at location I, (Fig 5.2) where gravel fined from medium-coarse (−5.2 phi) to fine gravel (−4.0 phi) over a distance of 15 m. Ashmore (personnal communication) found that similar fining trends, on other lobes sampled in the Sunwapta River, were statistically significant. It may be suggested that these lobes are basic units upon which size segregation occurs (Smith N.D. 1974, Bluck 1976, 1979 and Hein and Walker 1977).

5.3.3 Sorting Associated with Scours

Downstream of scours, sub-parallel bands of gravel of different size were observed trending in the former direction of flow. The coarsest gravel occurred in the lee of the deepest scour, and was flanked by bands of finer gravel for distances up to 10 m. The individual gravel bands also showed a slight downstream fining.

5.4 Longitudinal Trends in Sorting

The braid bars from the proximal and medial sub-reaches showed general fining, downstream and away from the active channels. No distinct fining trends were discernible over the bar surface of the distal sub-reach braid bar. It is suggested that this is a function of the complex development of the distal bar. As Bluck (1976) noted, elsewhere, rapid lateral changes in grain size were evident on all three bar surfaces.

With respect to the proximal and medial sub-reach braid bars, the coarsest gravel occurred where the beds of former channels were exposed and on the margins of active channels, particularly at the upstream ends of the bars. Bar head areas, tended to consist of gravel sheets, (as previously described), with grain sizes ranging from medium to coarse gravel (−4.9 phi to −5.7 phi). The bar tail regions showed extensive areas of fine to medium gravel (−4.0 phi to −4.9 phi) and sand. Many of the downstream fining trends resulted from a concentration of sand and fine gravel in the bar tail, although sand occurred as a waning flow deposit on all three bar surfaces. Similar fining trends have been recognised on complex braid bars by Ore (1964), Boothroyd and Ashley (1975) and Bluck (1979). Bluck (1979) suggested that the coarser gravel on the bar head was deposited at high stage, and the occurrence of finer downstream tail sediments was a reflection of deposition under lower stage. Ashmore (personnal communication), however, proposed that such downstream fining trends might be related to a single flow stage, the converging flow around the bar tail being of lower competence than the initial diverging flow at the bar head.

It is evident from the maps of the three braid bars that the range of grain sizes on the bar surfaces diminishes downstream. All the sediment size grades are evident on the proximal sub-reach braid bar, but only the finer grades occur on the distal sub-reach braid bar. The areal extent of the finer grain sizes, obviously, increases downstream.

5.5 Braid Bar Development

A hypothetical model of the formation of braid bars and associated sediment sorting patterns may be developed.This is based on a consideration of the descriptions of braid bar development by other workers and from the broad patterns of sediment sorting on, and the morphology of, the braid bars described above. The form of the initial development of braid bars is obscure, and two hypotheses are proposed. Both mechanisms have been observed by Ashmore (1979 and personal communication), in flume simulations, although he noted that a continuum may exist between them.

5.5.1 Initial Development

1) The initial development may occur around a nucleus in the form of an emergent unit bar (Ore 1964, Smith N.D. 1974, Bluck 1976, 1979, Hein and Walker 1977, and Ashmore 1979)(Figs 5.20 and 5.21) The final form of the braid bar in such a case is dependent on subsequent additions to and modifications of the original unit bar.

The morphology of the original unit bar is unlikely to be apparent in the final bar form, although certain features may be discernible. For instance, the braid bar may be dissected on emergence and, as noted by Krigstrom (1962), Williams and Rust (1969) and others, such channels produced by this dissection may be evident on the final bar form. If the original nucleus is a unit bar it is likely that it would show a distinct size grading, as described by Smith N.D. (1974), with a downstream and vertical fining, although these are unlikely to be apparent from the final bar form due to considerable modification. However, this nucleus may, as noted by Ore (1964) and Bluck (1979), form the coarsest part of the braid bar.

2) The initial form and size of a braid bar may alternatively be determined by patterns of channel migration, erosion and avulsion (Figs 5.19 and 5.20). Under such circumstances the outline of the braid bar is determined primarily by the divergence and convergence of channels in the area, and is the product of the dissection of gravel flats and unit bars which may have been deposited over considerable periods of time and under widely varying flow conditions. Although modifications to the outline of the braid bar may occur by addition to it these are relatively minor as compared to the situation where a braid bar develops around a nucleus.

There is considerable evidence on the three bars mapped to support this second hypothesis. The existence of type A channels on all three bar surfaces, and the occurrence of partially vegetated areas on the distal sub-reach braid bar, indicates that the bars were deposited by a complex sequence of events, possibly widely spaced in time, and not as a result of a single event.

5.5.2 Secondary Modification

The scale of the secondary modification of the initial bar form is likely to vary according to whether the bar develops from a nucleus or whether the outline of the bar is determined by channel migration and avulsion (Figs 5.19 and 5.20) However, it is suggested that the processes involved are basically similar.

The subsequent development of the braid bar occurs, as Ashmore (1979) outlined, by the lateral migration of adjacent channels. A broad similarity may be noted between the forms described by Ashmore (1979) and those discernible from the mapped braid bars. Whilst he described the morphology developing at a single reach discharge level, this may be extended to encompass deposition under fluctuating discharge levels.

1) Modifications as a result of lateral channel migration.

Deposition on the inside of the migrating channel occurs either in a form similar to a point bar (location A, Fig. 5.2) or in the form of small individual, overlapping lobes (location G, Fig 5.2) The two different forms of deposition, it is suggested, result from different flow conditions, the point bar developing where helicoidal flow is produced in the migrating channel, and the lobe forms developing as a result of deposition in expanding flow in a shallow channel. Sediment size patterns associated with the point bar show a decline in grain size away from the channel and to a certain extent downstream. The lobes exhibit downstream fining trends similar to those described for unit bars.

Where a single channel is migrating away from a bank, sucessive periods of accretion may result in the formation of a large lateral bar showing remnants of individual point bars, lobes and the former inner bank margins of the channels in which they formed. In the case where two channels diverge and rejoin around an initial nucleus, or an erosionally defined braid bar, for instance the proximal and medial sub-reach braid bars, comparison of the mapped braid bars with the descriptions of Ashmore (1979) illustrate the following;

a) Upstream migration of the flow diversion, deposition of gravel sheets on the bar head, and the formation of lobes or point bars just downstream of the apex.

b) The lateral migration of the channels in the mid-bar and bar-tail regions results in the attachment of lobes or point bars. A pattern of sequential lobe forms and abandoned channel margins may be evident, a result of successive depositional episodes, for example at location G, (Fig 5.2).

c) In active channels, mid-channel unit bars may continue to form and may later become attached to the bar itself.

2) Modifications due to overbank flows contemporaneous with lateral channel migration.

a) Overbank flows result in the formation of type B channels eroded into the bar surface, which commence in the bar head and converge in the bar tail.

b) Overbar flows may converge from both surrounding channels, or extend laterally from only one channel and together with contributions from the type B channels result in the formation of overlapping sheets and lobes on the bar tail (Gustavson, 1974).

c) The shallow flows over the bar surface may result in the formation of transverse ribs, particularly in areas of flow divergence.

The following sediment sorting patterns develop in association with the morphology described above.

1) Upstream portions of the bars and bar heads retain the size patterns of the original unit, modified by some upstream deposition of gravel. This area is relatively coarse as compared to the bar tail, although the coarsest gravel occurs at the channel margins.

2) The bar tail shows the finest grain size, often with extensive areas of sand due to the lower competence of converging flow over the bar surface (Ashmore, personal communication). Fining trends occur away from the source channels towards the individual lobes and sheets.

3) Lateral accretion features may show fining trends, as previously described.

5.5.3 Tertiary Modification

Modification of the surface may occur in the absence of large-scale deposition during a high discharge period subsequent to the formation of the main body of the bar complex (Figs 5.19 and 5.20). The modifications that occur are as follows;

1) The erosion of minor scours.

2) The formation of transverse ribs in fine gravel by shallow diverging flows.

3) The development of lineations in fine gravel downstream of protruding clasts or logs.

4) The development of levées by flows overtopping channel banks.

5) The emplacement of fine gravel and sand, for instance, in inter-rib

areas and abandoned channels.

The most extensive modifications to sediment sorting patterns results from the development of levées, which show definite fining trends away from the channels. This modification may obscure the patterns resulting from lateral channel migration. Some fining trends occur, as previously noted, in association with the development of transverse ribs and gravel lineations, although it is suggested that these are of limited significance in relation to broad sediment size trends.

5.5.4 Summary

Given the above conditions for the development of braid bars, it may be suggested that the surficial patterns of sediment sorting are largely the result of modifications of the bar surface (Figs 5.19 and 5.20). As a generalisation, the upstream channel margins will show the coarsest grain sizes, with extensive areas of coarse gravel occurring near the upstream end of the bar. Sediment sizes fine downstream and away from the active channels, the finest sediment being located on the bar tail. The bar structure itself will be largely unaffected and vertical size sorting trends are likely to reflect patterns of accretion, probably a complex juxtaposition of deposits from earlier multiple depositional episodes and deposits by lateral accretion. It is unlikely that such definable products of bar surface modification as lobes are extensively preserved in the stratigraphic record.

5.6 Between-Site Variations in Grain Size.

The statistical analyses of Chapter Four showed considerable variability in grain size within individual sampling transects located at the same distance downstream. Similarly, Church and Kellerhals (1978) noted significant within-site variance in their study of gravel sediments of the Peace River. Attempts were made in both studies to eliminate such variability by stratifying the samples geomorphically and taking only samples from bar heads or channel margins. The maps presented in this chapter show that considerable local variability in grain size occurs on gravel bars, and, therefore, it is not surprising that significant variance was noted about the statistical relationships. Whilst generalised patterns of sediment size sorting may be predicted using the model developed, it is

FIG. 5.19 HYPOTHETICAL MODEL OF BRAID BAR DEVELOPMENT: 1

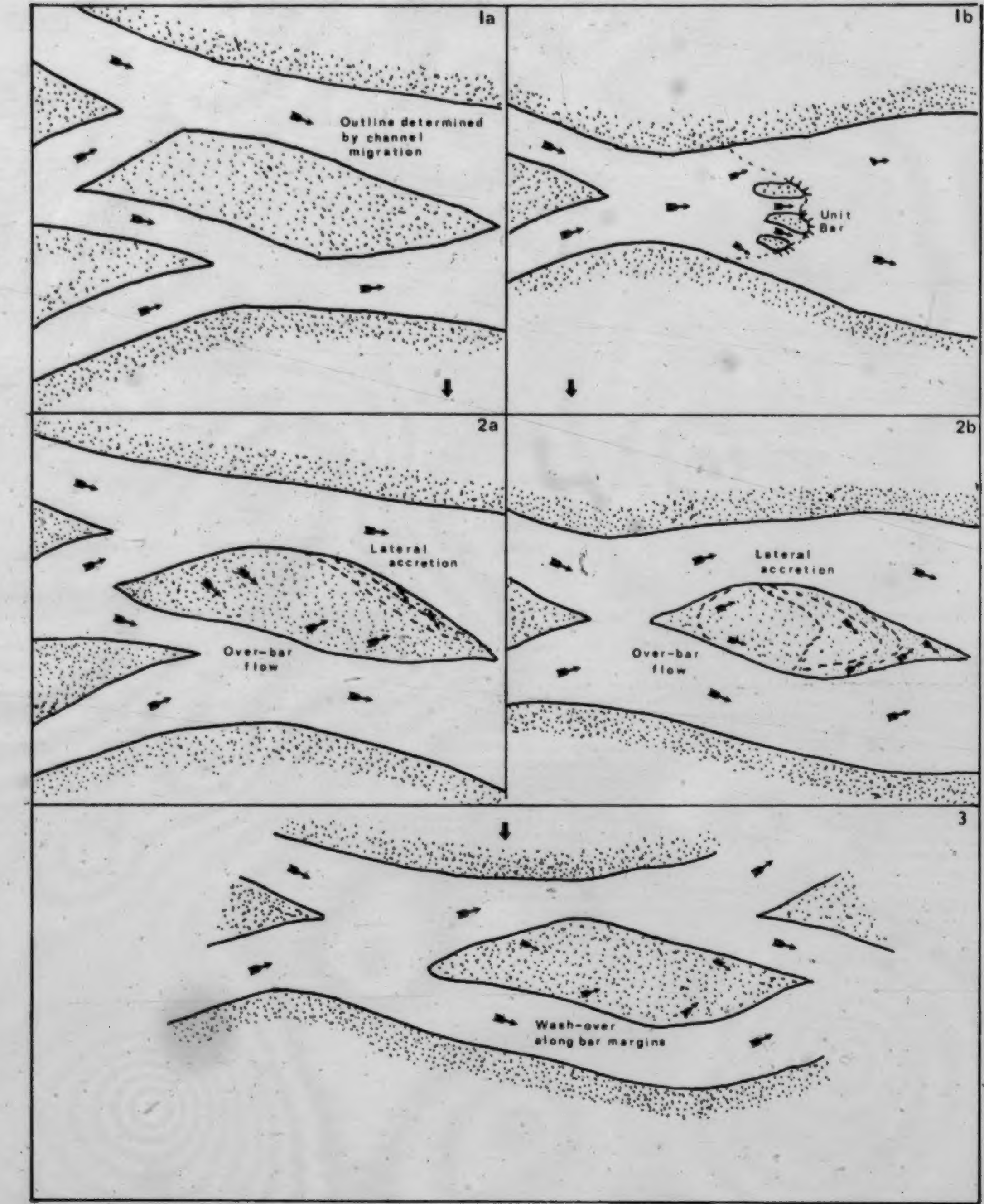
1a
Outline determined by channel migration
1b
Unit Bar
2a
Lateral accretion
Over-bar flow
2b
Lateral accretion
Over-bar flow
3
Wash-over along bar margins

Fig 5.20

HYPOTHETICAL MODEL OF BRAID BAR DEVELOPMENT:2

Two alternative hypotheses for braid bar development are illustrated here. Alternative a. shows the development of a bar from a previously deposited gravel area. Alternative b. shows the development of a bar around a nucleus, such as a unit bar. Three stages are illustrated for each hypothesis. It is suggested that the third stage is common to both hypotheses.

1a: Delimitation of braid bar outline by channel migration and avulsion.

1b: Development of a unit bar in a flow expansion. This forms a nucleus for later braid bar development.

2a: Modification of gravel area by overbar flow and by lateral accretion along the banks of the bar. Overbar flow results in such forms as, Type B channels, lobes on the bar surface and transverse ribs.

2b: Growth of unit bar by accretion at upstream, downstream and lateral margins by flow diverging around the bar head and converging around the bar tail. The bar surface is extensively modified by overbar flow, producing, for instance Type B channels, lobes on the bar surface and transverse ribs.

3: Minor modification of the bar surface by overbank flows at high stages after the emplacement of the bar resulting in the development, for instance, of levées and and lineated gravel.

suggested that actual sediment sizes and depositional patterns vary randomly between bars. The use of a geomorphic stratification in the original sampling is justified at the broad level of the model, but with regard to the above observations it is unlikely that all within-site variation can be eliminated.

5.7 Relative Grain Sizes on Bar Surfaces and Channels

Ballantyne (1978) noted, from a trend surface analysis of braided river sediments, that channel and bar surface sediments showed a difference in relative grain sizes, with bar surface sediments being, in general, finer than channel sediments. Sediments in both depositional locations fined downstream. However, the trends also converged downstream. In the current study, it was noted that the range of grain sizes decreased downstream, with all grain sizes being observed on the bar located in the proximal sub-reach, but only a limited range occurring on the bar located in the distal sub-reach. The relative area of the finer grain sizes increased downstream. It is suggested that the overall diminution of grain sizes in the reach, as discussed in Chapter Four, is a limiting factor on maximium grain size. However, whilst the overall competence to transport sediment decreases downstream, a range of local competencies occurs. Under certain circumstances, low competence flows in the proximal zones result in the emplacement of fine gravel on bar surfaces. It is suggested that the converging trends exhibited by channel and bar surface sediments in Ballantyne's (1978) study are the result of his sampling of fine gravel from proximal and medial bar surfaces and a diminishing of grain size downstream.

6. SUMMARY AND CONCLUSIONS

6.1 Size-Distance Relationships

Analysis of the variation in grain size in a short, braided, reach of the Sunwapta River, shows a departure from the expected model of a uniform, exponential, downstream decline in grain size. The downstream decline in grain size is best described by four separate exponential functions of size against distance corresponding to each of the sub-reaches defined by tributary locations. Whilst a single exponential function may be fitted to the data for the whole reach, there would be considerable variation about the relationship, as noted elsewhere by Church and Kellerhals (1978) and Knighton (1980, 1982). Even in an apparently homogeneous reach, with only minor tributary inflow, upstream of the Diadem Creek alluvial fan, there are deviations from the expected exponential form. The variation is statistically attributable to two components; variability within sampling transects; and variability between sub-reaches. The latter source of variability can be partially, but not solely, attributed to the effect of tributary inputs.

The effect of tributary inputs to the reach varies according to the sediment size and discharge of an individual tributary. Where the sediment input is significantly large, and the clast sizes are coarser than those of clasts in the main reach, the following geomorphological effects are discernible;

1) the main channel slope decreases upstream of the tributary, and increases downstream of the tributary.

2) grain size increases downstream of the tributary

3) downstream diminution rates increase as a result of differential transport. Upstream this is due to a reduction in competence and downstream this results from the lag deposition of the coarse fractions of the tributary input.

It is suggested that the tributary input has its own rate of diminution, the size decrease taking an exponential form, superimposed on the general decline in grain size.

Comparison of the limestone diminution coefficients for the separate sub-reaches of the study area, with an average diminution coefficient from other Albertan rivers, shows that the processes operating to produce the downstream decline in grain size are not uniform over the reach. In the proximal and medial sub-reaches the relatively low diminution coefficients indicate that differential transport is of less importance than would be expected in a braided river environment. It is probable that some form of degradation is occurring, particularly in the proximal sub-reach. Morphological evidence from proglacial areas, located upstream, indicates that sediment input to the river has been reduced, as incision of proglacial outwash adjacent to the Athabasca and Stutfield Glaciers has occurred. In the proximal sub-reach the active area lies 40-50 cm below an abandoned gravel surface with extensive vegetation cover. The surface is well above the annual peak flow stage and the undisturbed nature of large borrow pits, excavated in 1959, indicates that the surface has not been reworked since. The active area has an east to west slope and the water level of the main channel is 1 to 1.5m below the vegetated surface. Morphological evidence for degradation is supported by a comparison of the diminution coefficients obtained for the proximal sub-reach. These are considerably lower than those obtained in other studies for aggrading rivers (Appendix 6).

The higher diminution coefficients in the distal and inter-fan sub-reaches indicate that differential transport is an effective process upstream and downstream of large tributaries and alluvial fans (as previously noted). Observations indicate that the influence of the tributary alluvial fans on slope and grain size is residual as they are not, at present, prograding into the Sunwapta River. In the absence of a coarse sediment input, the fan controlled base of the reach is probably being lowered. Consequently, given the reduced sediment input into the reach from upstream and the lowering base level at both alluvial fans, the study reach as a whole may be undergoing limited degradation. However, the amount of incision beneath older surfaces is small and thus degradation does not seem to be rapid in comparison to the rate of incision in the headwaters of the Sunwapta River. Here, immediately downstream of Sunwapta Lake, terraces of 2 to 3 m have developed in approximately 30 to 40 years.

The diminution of grain size in the studied reach varies between lithologies, the limestone having a lower diminution coefficient than either the quartzitic lithological group or the true quartzites. This is a major anomaly, although not statistically significant, which cannot be satisfactorily accounted for. However, a comparison in the differences in the mean grain size of the limestone and quartzitic components of a small number of samples at the head of the proximal sub-reach suggests that a coarse quartzitic component is introduced at this point. Low roundness values for the quartzitic component also suggest that the high diminution coefficients may be the result of size reduction by fracturing.

Variation about the relationship between grain size and downstream distance, also resulted from within-transect, site scale variability. Whilst statistical analysis could not isolate the cause of this within-transect variability, detailed examination of sediment size variations over three selected braid bars indicated that there was considerable variation in grain size over relatively short distances. It is suggested that, although some attempt was made to stratify the sampling by collecting the samples from bar heads or coarse gravel from channel margins, the significant variation in grain size noted within the sampling transects was a result of local, site-scale variation rather than, for instance, a trend in grain size across the reach.

Grain size diminution in the studied reach may be attributed to a variety of processes. The low diminution coefficients for certain sub-reaches indicate that attrition is a significant factor in causing size reduction. The size reduction due to attrition for the limestone component of the river sediments seems to result from surface abrasion, as the clasts are generally well rounded and show little evidence of fracturing. However, the angular nature of the quartzitic sediments, and the higher diminution coefficients obtained for the quartzites strongly suggests that attrition also results from fracturing. The unstable nature of the bed and banks in the reach means that the sediments are highly mobile and it is unlikely that attrition *in situ* is important relative to attrition in transport.

The high values of the diminution coefficients, particularly in more distal areas of the study reach indicate that differential transport is an important process in causing sediment size reduction. The downstream improvement in sediment sorting shows that the range of grain sizes at a given location becomes more restricted with distance. The existence of fine grain sizes on braid bars in the proximal sub-reach partially confirms that the coarsest fractions are being preferentially deposited. With regard to the work of Laronne and Carson (1976) and Koster (1977), it is probable that this is due to declining competence with distance downstream and slower transport velocities for the coarser fractions. The finer fractions are likely to be preferentially transported, in time, as a result of being winnowed out from deposits of coarser clasts by flows of high frequency, but which are incapable of transporting the coarse sediment. However, the more rapid transport velocities for intermediate sized clasts (Koster 1977) may result in them being the first to be deposited and buried, and the last to be exhumed by scour. In consequence they would have a slower transport velocity in time. Therefore size diminution due to differential transport seems to be the result of declining downstream competence, a lower frequency and velocity of transport of coarse clasts, and the burial of intermediate sized clasts.

Sediment sizes over braid bars are limited in range only by the availability of large clasts, with fine grain sizes occurring on all the bar surfaces sampled. The existence of fine grain sizes on the more proximal braid bars is the result of the flows, over parts of the bar surface removed by relative height or distance from the active channels, being of low competence. The areal proportion of the finer grain sizes on the bar surfaces increases downstream. Due to the decline in maximum grain size downstream the range of grain sizes is correspondingly more restricted in a downstream direction. The sampling of fine grain sizes on proximal braid bars is a probable explanation for Ballantyne's (1978) observation that bar surfaces fined downstream less rapidly than channel sediments.

6.2 Sediment Sorting-Distance Relationships

Sediment sorting improves downstream, although considerable variation occurs around the sorting–distance relationships. Minor tributaries seem to have little influence on sediment sorting. However, the caliber of the input at Diadem Creek causes an initial reduction in sediment sorting, and evidence presented here indicates that separate linear or possibly exponential trends (Mills 1979) in sorting occur in reaches defined by major tributaries. Such trends seem to result from the preferential deposition of the coarsest fractions of the sediment load, resulting in a progressive reduction in the range of sediment sizes occurring at a single location. There is no evidence from the present study that variations in sorting can best be described by a cosine function as proposed by Knighton (1980).

6.3 Clast Morphology

6.3.1 Roundness

Roundness increases downstream, with two separate trends being discernible in the study reach up and downstream of Diadem Creek. Whilst Diadem Creek has a similar effect to that of tributaries in the River Noe (Knighton 1982) in introducing clasts of lower roundness to the reach, the other tributaries seem to have little effect on trends in roundness. Roundness variation with distance upstream of Diadem Creek exhibits two differing relationships. Over the first kilometre there is a rapid increase in roundness, whereas downstream roundness increases more slowly with distance, although considerable variation is evident around this general trend. This relationship is similar to those observed by Krumbein (1942b) and Plumley (1948) and may be attributed to the rapid rounding of large angular particles over the first kilometre or so, with the subsequent slower rates of decline occurring as the particles become more rounded and smaller in size. Similar processes may be in operation downstream of Diadem Creek, with only the initial, rapid decline in roundness away from the source being evident due to the short distance of travel.

6.3.2 Clast Form

Evidence to support sediment sorting by clast form is unconvincing for the study reach upstream of Diadem Creek. This finding is at variance with those of other studies of braided rivers. Bradley *et al.* (1972) noted a distinct preferential sorting of flatter, disc-shaped clasts. Given that sorting by size occurs in the reach, as shown by the contribution to the diminution coefficients from differential transport, this is unexpected. Trends in grain shape may be confounded by the introduction of fresh material from the Wooley and Beauty Creek tributaries although this is not evident from the distance-clast form graphs. Changes in clast form are more distinct downstream of the Diadem Creek fan. However, the trends exhibited are at variance with many previous field studies (Unrug 1957, Bluck 1964, Bradley *et al.* 1972, Knighton 1982) as there is a presumed preferential transport of more spherical or roller-like clasts. Some agreement is noted with the conclusions of Lane and Carlson (1954), who found that spherical clasts with the same weight as disc shaped clasts were more easily transported due to the imbrication of the flatter clasts in the bed, and Koster (1977) who noted that prolate forms were more easily transported when clast size-depth ratios were high.

6.4 Variations in Sediment Sizes on Braid Bars.

From maps of selected braid bars located in the gravel areas of the study reach upstream of Diadem Creek, common morphological features, such as minor channels and gravel sheets, were noted. Local trends in sorting were recognised over specific features such as point bars, lobes on the bar surface and levees. Such features tended to fine away from active or formerly active channels. The bars also showed a tendency to fine in a downstream direction. This however was largely the result of the deposition of fine gravel and sand on the bar tail. The examination of these morphological features and a consideration of previous work led to the development of a hypothetical model of braid bar evolution with three essential elements;

1) The formation of a nucleus in the form of an emergent unit bar or the delimitation of the outline of the bar by channel migration and avulsion in an area of previously deposited gravel. These are suggested to be the extremes in a continuum and the initial phase of bar development may occur as a combination of the two.

2) The modification of the original area by lateral accretion and overbank flows causing the formation of scour channels, lobes and many of the sorting trends away from the channels.

3) The limited modification of the surface by small over bank flows at later high flow stages.

Many of the sorting trends on braid bars seem to be the result of the reorganization of previously emplaced sediments by overbank flows, and the sorting trends developed in the initial period of bar emplacement are not evident at the surface. However, in a stratigraphic sequence it is probable that sedimentary structures developed during the initial periods of bar development are best preserved. The sediment sorting trends, as described, are likely to be of minor significance in a stratigraphic sequence as they develop as a surface veneer.

This hypothetical model is based on observation of final forms and cannot be regarded as a definitive model of braid bar development. Further field and laboratory observations of braid bars during formation is required before a sequence of development can be realistically inferred.

6.5 Channel Pattern Development

Channel pattern, as described in Chapter 1, shows a systematic variation downstream, with transition from a coarse gravel braided to a sandy braided pattern both upstream and downstream of Diadem Creek. Upstream of Diadem Creek an anastomosed channel pattern occurs between the gravel and sandy braided sections. Rice (1979) also noted that channel behaviour varied downstream over the Beauty Creek flats and concluded that the most influential factor in controlling this variation was the median grain size of the material in the channel bed and banks. He suggested that the decreasing grain size and increasing percentage of sand downstream led to increased bank stability in the lower reaches. In the context of the present study, given discharge is relatively constant in a downreach direction, the change in channel pattern seems to be the result of an interaction between slope and grain size; the high slope and coarse grain size resulting in a gravel braided channel pattern, and low slope and fine grain size resulting in an anastomosing or sandy braided pattern.

The anastomosed channel pattern seems to develop in a transition between the higher slope proximal areas and the lower slope distal areas of the two reaches in a zone affected by the backwater of the alluvial fans and beyond which gravel is not transported. It seems likely as Smith, D.G, and Smith, N.D. (1981) suggested, that the amount of fines in the deposited load (and overbank vegetation) are sufficient to maintain stable resistant banks. Gravel accumulation occurs within the channels, and fines are deposited in overbank areas. The major difference between the anastomosed and sandy braided sections is that the latter lacks a gravel bed. Bed armouring by imbricated gravel probably results in more stable beds in the anastomosed section, whereas the easily erodible sand beds in the sandy braided section allow large scale bed movement and bar formation between the stabilised banks. The transitional section immediately upstream of the anastomosed section is similar to those recognised by Smith, D.G and Smith, N.D

(1981). They proposed that, such channel patterns resulted from the encroachment of a gravel braided pattern on an anastomosed section.

6.6 Applications with Respect to Facies Analysis

Although it has been shown that the reach of the Sunwapta River studied cannot be regarded as currently aggrading the results may be applied in the interpretation of ancient braided river sequences. Assuming Walther's (1894) law, [2] vertical transition from proximal to distal sequences, the following changes in grain size and shape can be anticipated on the basis of this study:

1) The size of the coarsest units should decrease systematically upwards.

2) The range of grain sizes should also decrease upwards with sands and fine gravels occurring in both the proximal and distal sequences, although the relative volume of the sands and fine gravels in the proximal sequences will be considerably less than in the distal sequences.

3) Gravel clasts should, on average, become more rounded upwards.

The current study shows that the transition from proximal to distal sequences, in a braided river valley fill, cannot be related to distance from a single source. It is evident that the progradation of alluvial fans is an important influence on reach slope, grain size, channel pattern and, as a consequence in an aggrading situation, on sedimentary sequences. As a hypothetical example, in a reach where the rate of sediment input from upstream remains relatively constant , the rapid aggradation of an alluvial fan would result in the upstream extension of a backwater curve. Consequently there would be an upstream transgression of distal channel patterns, resulting in the development of a proximal to distal fining-upwards succession. Downstream, however, the increase in slope and grain size due to the aggradation of the alluvial fan would result in the downstream migration of proximal channel patterns and the progradation of proximal sequences over more distal sequences, resulting in a distal to proximal coarsening-upwards succession.

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[2] This assumes that in an aggrading situation, "facies occurring in a conformable vertical sequence were formed in laterally adjacent environments and that facies in vertical (gradational) contact must be the product of geographically neighbouring environments." (Reading 1978, p 4)

The above example, and the present grain-size study, illustrate that widely differing successions may result over a relatively short distance within a braided river valley fill. In foreland molasse alluvium, as a result of its piedmont setting, no such complicating effects would be evident. It should also be noted that ancient gravelly alluvium often accumulated without glacial influence and the grain size patterns demonstrated in this previously glaciated catchment may not be replicated. Whilst the comments here have been directed towards the interpretation of trends in vertical sequences, the statements are equally applicable to the palaeogeographical interpretation of, for instance, post-glacial deposits of alluvium. In conclusion, the results outlined in this thesis show that proximal to distal interpretions of gravelly alluvium, both in a stratigraphic or in a paleogeographic sense, should be used with caution.

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APPENDIX 1

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C      COBLAN PROGRAM. WRITTEN BY M. CHURCH (1970), MODIFIED BY M. DAWSON (1982)
C      PROGRAM CALCULATES MEAN SIZE OF A,B,C AXES, CAILLEUX ROUNDNESS, MODIFIED
C      CAILLEUX FLATNESS, MAXIMUM PROJECTION SPHERICITY AND 2ND, 3RD, 4TH
C      MOMENTS OF THESE MEASURES. OUTPUT INCLUDES RANKED (B AXIS SIZE) TABLE
C      OF INDIVIDUAL CLAST CHARACTERISTICS; FREQUENCY DISTRIBUTION AND
C      CUMULATIVE FREQUENCY OF SAMPLE MEASURES; MEAN SIZE OF A SPECIFIED
C      NUMBER OF LARGE COBBLES; MEDIAN GRAIN SIZE AND TRASK SORTING. ZINGG
C      SHAPE AND ROCK TYPE ARE CLASSIFIED.
C      LIMITATIONS: CLASTS SHOULD HAVE A B-AXIS SIZE GREATER THAN 2MM.
C                 : MAXIMUM SAMPLE SIZE 250 CLASTS.
C      DATA DECK ASSEMBLY.
C       1)FORMAT CARD FOR DATA, WHICH MUST BE COMMON FOR ALL SAMPLES IN THE
C      RUN
C       2)HEAD CARD WITH NAME OF SAMPLE IN A6 (COLS 1-7), SIZE OF SAMPLE
C      (N) IN I4 (COLS 9-12), AND X LARGEST TO BE ABSTRACTED (NBIG) IN I3
C      (COLS 13-15). OPTIONAL CONVERSION TO PHI MEASURES IS PROVIDED FOR
C      MAIN SAMPLE PARAMETERS IF COL 17 IS NON-ZERO.
C       3)DATA CARDS, 1 FOR EACH CLAST IN EACH SAMPLE, GIVING CLAST NUMBER,
C      A,B,C AXES AND MINIMUM RADIUS OF CURVATURE(MM), AND COBBLE TYPE CODE.
      DIMENSION FMT(12),NO(250),D(6,250),IT(250)
      DIMENSION DIST(9),CUDIST(9),PDIST(10,3),ITYP(5,10),XTYP(9)
      DIMENSION SUM(6,4), XMO(6,5)
      READ(5,1)FMT
1     FORMAT(12A4)
47    READ(5,2)NAME,N,NBIG,IPHI
2     FORMAT(A6,2X,I4,I3,1X,I1)
      IF(N.EQ.0)GO TO 101
      WRITE(6,3)NAME,N
3     FORMAT(1H1,12HSAMPLE NO.  ,A6,10X,13HSAMPLE SIZE =,I4)
      WRITE(6,17)
17   0FORMAT(1H0,40X,39HSAMPLE RANKED BY INTERMEDIATE AXIS SIZE/
     1'RANK    SAMPLE NO.       A AXIS        B AXIS       C AXIS ',
     2'    ROUNDNESS        FLATNESS      SPHERICITY        TYPE'/)
      DO 5 I=1,9
5     DIST(I)=0.0
      DO 6 I=1,6
      DO 6 J=1,4
6     SUM (I,J)=0.0
      DO 7 I=1,10
      DO 4 K=1,5
4     ITYP(K,I)=0
      DO 7 J=1,3
7     PDIST(I,J)=0.0
C     READ DATA, CALCULATE PARAMETERS, FORM SUMS AND DISTRIBUTIONS
      DO 8 J=1,N
8     READ(5,FMT)NO(J),(D(I,J),I=1,4),IT(J)
      CALL RANK(D,NO,IT,N)
      DO 11 J=1,N
      D(4,J)=(2.0*D(4,J))/D(1,J)
      D(5,J)=(2.0*D(3,J))/(D(1,J)+D(2,J))
      D(6,J)=((D(3,J)*D(3,J))/(D(1,J)*D(2,J)))**0.333333
      DO 15 I=1,6
      SUM(I,1)=SUM(I,1)+D(I,J)
      X2=D(I,J)*D(I,J)
      SUM(I,2)=SUM(I,2)+X2
      X3=X2*D(I,J)
      SUM(I,3)=SUM(I,3)+X3
      X4=X3*D(I,J)
15    SUM(I,4)=SUM(I,4)+X4
      DIV=4.0
      I=1
14    IF(DIV-D(2,J))12,12,13
12    I=I+1
      IF(I.EQ.9)GO TO 13
      DIV=DIV*2.0
      GO TO 14
13    DIST(I)=DIST(I)+1.0
      DO 94 I=4,6
      DI=0.1
      L=1
43    IF(DI-D(I,J))49,49,18
49    L=L+1
      IF(L.EQ.10)GO TO 18
      DI=DI+0.1
      GO TO 43
18    K=I-3
94    PDIST(L,K)=PDIST(L,K)+1.0
      WRITE(6,91)J,NO(J),(D(I,J),I=1,6),IT(J)
91    FORMAT(1H ,I4,6X,I4,6X,3(4X,F8.1),3(9X,F5.3),9X,I2)
      K=IT(J)
      ZING1=D(2,J)/D(1,J)
      ZING2=D(3,J)/D(2,J)
      IF(ZING1.GT.0.666667)GO TO 9
      IF(ZING2.GT.0.666667)GO TO 10
      ITYP(1,K)=ITYP(1,K)+1
      GO TO 11
10    ITYP(2,K)=ITYP(2,K)+1
      GO TO 11
9     IF(ZING2.GT.0.666667)GO TO 92
      ITYP(4,K)=ITYP(4,K)+1
      GO TO 11
92    ITYP(3,K)=ITYP(3,K)+1
11    CONTINUE
      DO 131 J=1,9
      DO 131 I=1,4
131   ITYP(5,J)=ITYP(5,J)+ITYP(I,J)
      DO 132 I=1,5
      DO 132 J=1,9
132   ITYP(I,10)=ITYP(I,10)+ITYP(I,J)
C     CALCULATION AND PRINT OUT OF MOMENTS
      WRITE(6,20)
20     FORMAT(1H0,58X,15HMOMENT MEASURES)
      EN=N
      EN1=EN-1.0
      DO 21 I=1,6
      XMO(I,1)=SUM(I,1)/EN
      XM=XMO(I,1)*XMO(I,1)
      XMO(I,2)=(SUM(I,2)-EN*XM)/EN1
      XMO(I,3)=SQRT(XMO(I,2))
     0XMO(I,4)=(EN*(SUM(I,3)-3.0*SUM(I,2)*XMO(I,1)+(2.0*EN)*XMO(I,1)*XM))
     1)/(XMO(I,2)*XMO(I,3)*(EN-2.0)*EN1)
21   0XMO(I,5)=(EN*((EN+1.0)*(SUM(I,4)-4.0*SUM(I,3)*XMO(I,1)+6.0*SUM(I,2)
     1)*XM-3.0*EN*XM*XM))-(3.0*XMO(I,2)*XMO(I,2)*EN1*EN1*EN1))/(XMO(I,2)
     3*XMO(I,2)*EN1*(EN-2.0)*(EN-3.0))
      WRITE(6,22)(XMO(I,1),I=1,6)
22    FORMAT(1H0,4HMEAN,16X,3(4X,F8.3),3(9X,F5.3))
      WRITE(6,23)(XMO(I,2),I=1,6)
23    FORMAT(1H0,8HVARIANCE,12X,3F12.3,3F14.3)
      WRITE(6,24)(XMO(I,3),I=1,6)
24    FORMAT(1H0,18HSTANDARD DEVIATION,2X,3F12.3,3F14.3)
```

```
       WRITE(6,25)(XMO(I,4),I=1,6)
 25    FORMAT(1HO,17HSTANDARD SKEWNESS,3X,3F12.3,3F14.3)
       WRITE(6,26)(XMO(I,5),I=1,6)
 26    FORMAT(1HO,17HSTANDARD KURTOSIS,3X,3F12.3,3F14.3)
       IF(IPHI.EQ.O)GO TO 48
       CALL PHI(XMO)
 48    WRITE(6,27)
 27   OFORMAT(////42X,35HSAMPLE DISTRIBUTION BY SIZE CLASSES/
      1'                   2-4          4-8           8-16          16-32',
      2'     32-64        64-128       128-256        256-512     GT.512'/ )
       WRITE(6,30)(DIST(I),I=1,9)
 30    FORMAT(1HO,9HFREQUENCY,6X,9(4X,F7.1))
       DO 31 I=1,9
 31    DIST(I)=DIST(I)/EN
       WRITE(6,32)(DIST(I),I=1,9)
 32    FORMAT(1HO,17HPROPORTIONAL FREQ,9(6X,F5.3))
       CUDIST(1)=DIST(1)
       DO 33 I=2,9
       J=I-1
 33    CUDIST(I)=DIST(I)+CUDIST(J)
       WRITE(6,34)(CUDIST(I),I=1,9)
 34    FORMAT(1HO,15HCUM. PROP. FREQ,2X,9(5X,F6.3))
       WRITE(6,16)
 16   OFORMAT(////47X,26HDISTRIBUTION OF PARAMETERS//20X,98H 0.0-0.1   O.
      11-0.2   0.2-0.3   0.3-0.4   0.4-0.5   0.5-0.6   0.6-0.7   0.7-0.8
      2 0.8-0.9   0.9-1.0/ )
       DO 28 I=1,10
       DO 28 J=1,3
 28    PDIST(I,J)=PDIST(I,J)/EN
       WRITE(6,29)(PDIST(I,1),I=1,10)
 29    FORMAT(1HO, 9HROUNDNESS,8X,10(5X,F5.3))
       WRITE(6,50)(PDIST(I,2),I=1,10)
 50    FORMAT(1HO, 8HFLATNESS,9X,10(5X,F5.3))
       WRITE(6,40)(PDIST(I,3),I=1,10)
 40    FORMAT(1HO, 10HSPHERICITY,7X,10(5X,F5.3))
 C     COMPUTE MEAN OF THE 20 LARGEST CLASTS
       SUMBIG=0.0
       DO 35 I=1,NBIG
 35    SUMBIG=SUMBIG+D(2,I)
       ENBIG=NBIG
       XMNBIG=SUMBIG/ENBIG
       WRITE(6,36)NBIG,XMNBIG
 36    FORMAT(////8H MEAN OF,I4,18H LARGEST COBBLES =,F8.3,3H MM)
 C     OPTIONAL PERCENTILE ANALYSIS FOR TRASK COEFFICIENT.
       ENCH=EN*0.25
       NCH=N/4
       ENC=NCH
       REF=ENCH-ENC
       IF(REF.LT.0.24)GO TO 140
       IF(REF.LT.0.49)GO TO 141
       IF(REF.LT.0.74)GO TO 143
       N2=(N+1)/2
       DM=D(2,N2)
       N4=(N+1)/4
       Q1=D(2,N4)
       N6=N2+N4
       Q3=D(2,N6)
       GO TO 142
 140   N2=N/2
       N4=N/4
      N3=N2+1
      DM=(D(2,N2)+D(2,N3))/2.0
      N5=N4+1
      Q1=(3.0*D(2,N4)+D(2,N5))/4.0
      N6=N2+N4
      N7=N6+1
      Q3=(D(2,N6)+3.0*D(2,N7))/4.0
      GO TO 142
  141 N2=(N+1)/2
      DM=D(2,N2)
      N4=N/4
      N5=N4+1
      Q1=0.5*D(2,N4)+0.5*D(2,N5)
      N6=N2+N4
      N7=N6+1
      Q3=0.5*D(2,N6)+0.5*D(2,N7)
      GO TO 142
  143 N2=N/2
      N3=N2+1
      DM=0.5*D(2,N2)+0.5*D(2,N3)
      N4=N/4
      N5=N4+1
      Q1=0.25*D(2,N4)+0.75*D(2,N5)
      N6=N2+N4
      N7=N6+1
      Q3=0.75*D(2,N6)+0.25*D(2,N7)
      GO TO 142
  142 QR=Q1/Q3
      TR=SQRT(QR)
      WRITE(6,37)DM
   37 FORMAT(1H0,21HMEDIAN COBBLE SIZE IS,F8.3,3H MM)
      WRITE(6,38)TR
   38 FORMAT(1H0,28HTRASK SORTING COEFFICIENT IS,F8.3)
      WRITE(6,39)
   39 FORMAT(////15X,29HSHAPE AND TYPE CLASSIFICATION/62H TYPE          1
     1  2     3     4     5     6     7     8     9  TOTAL /12H ZINGG SHAPE)
      WRITE(6,41)((ITYP(I,J),J=1,10),I=1,5)
   41 FORMAT(1H0,5HBLADE,3X,10I5/7H0ROLLER,2X,10I5/9H0SPHEROID,10I5/
     15H0DISC,4X,10I5/6H0TOTAL,3X,10I5)
      DO 45 I=1,9
      XTYP(I)=ITYP(5,I)
   45 XTYP(I)=XTYP(I)/EN
      WRITE(6,46)(XTYP(I),I=1,9)
   46 FORMAT(1H0,9HFREQUENCY,9F5.2)
      GO TO 47
  101 CONTINUE
      STOP
      END
      SUBROUTINE RANK(D2,NO2,IT2,N)
      DIMENSION D(6,250),D2(6,250),NO(250),NO2(250),IT(250),IT2(250)
      DO 82 I=1,N
      BIG=0.0
      DO 81 J=1,N
      IF(D2(2,J).LE.BIG)GO TO 81
      BIG=D2(2,J)
      K=J
   81 CONTINUE
      D(2,I)=BIG
      NO(I)=NO2(K)
      IT(I)=IT2(K)
```

```
              D(1,I)=D2(1,K)
              D(3,I)=D2(3,K)
              D(4,I)=D2(4,K)
     82       D2(2,K)=0.0
              DO 83 J=1,N
              NO2(J)=NO(J)
              IT2(J)=IT(J)
              DO 83 I=1,4
     83       D2(I,J)=D(I,J)
              RETURN
              END
              SUBROUTINE PHI(XMO)
              DIMENSION XMO(6,5)
              DO 61 I=1,6
              XMO(I,4)=XMO(I,4)/6.0
              XMO(I,1)=-(ALOG(XMO(I,1))*1.443)
     61       XMO(I,3)=-(ALOG(XMO(I,3))*1.443)
              WRITE(6,62)
     62       FORMAT(1H0,44X,31HPHI STATISTICAL MOMENT MEASURES)
              WRITE(6,63)(XMO(I,1),I=1,6)
     63       FORMAT(1H0,4HMEAN,16X,3(6X,F6.3),3(8X,F6.3))
              WRITE(6,65)(XMO(I,3),I=1,6)
     65       FORMAT(1H0,13HPHI DEVIATION,7X,3F12.3,3F14.3)
              WRITE(6,66)(XMO(I,4),I=1,6)
     66       FORMAT(1H0,12HPHI SKEWNESS,8X,3F12.3,3F14.3)
              RETURN
              END
End of file
```

APPENDIX 2

```
C          PROGRAM ADAPTED BY M. DAWSON FROM ORIGINAL WRITTEN BY M. CHURCH (1970).
C          PROGRAM CALCULATES PHI MEAN SIZE OF A,B,C AXES AND 2ND, 3RD, 4TH
C          MOMENTS. CONVERTS ORIGINAL MM MEASUREMENTS OF INDIVIDUAL CLASTS INTO
C          PHI SIZES BY THE CONVERSION LOG (NORMAL) B (GRAIN SIZE) * 1.443.
C          OUTPUT ALSO INCLUDES VALUES FOR ROUNDNESS, FLATNESS, SPHERICITY IN
C          PHI MEASUREMENTS.
C          FOR LIMITATIONS AND DATA INPUT PLEASE SEE LISTING OF THE MAIN PROGRAM.
           DIMENSION FMT(12),NO(250),D(6,250),IT(250)
           DIMENSION SUM(6,4), XMO(6,5)
           READ(5,1)FMT
  1        FORMAT(12A4)
  47       READ(5,2)NAME,N
  2        FORMAT(A6,2X,I4,5X)
           IF(N.EQ.0)GO TO 101
           WRITE(6,3)NAME,N
  3        FORMAT(1H1,12HSAMPLE NO.    ,A6,10X,13HSAMPLE SIZE =,I4)
           DO 6 I=1,6
           DO 6 J=1,4
  6        SUM(I,J)=0.0
           DO 8 J=1,N
           READ(5,FMT)NO(J),(D(I,J),I=1,4),IT(J)
           DO 300 II=1,4
  300      D(II,J)= -(ALOG(D(II,J))*1.443)
           D(4,J)=(2.0*D(4,J))/D(1,J)
           D(5,J)=(2.0*D(3,J))/(D(1,J)+D(2,J))
           D(6,J)=((D(2,J)*D(3,J))/(D(1,J)*D(1,J)))*0.333333
           DO 15 I=1,6
           SUM(I,1)=SUM(I,1)+D(I,J)
           X2=D(I,J)*D(I,J)
           SUM(I,2)=SUM(I,2)+X2
           X3=X2*D(I,J)
           SUM(I,3)=SUM(I,3)+X3
           X4=X3*D(I,J)
  15       SUM(I,4)=SUM(I,4)+X4
  8        CONTINUE
           WRITE(6,20)
  20     OFORMAT(1HO,50X,15HMOMENT MEASURES//
         1'                                  A-AXIS      B-AXIS       C-AXIS',
         2'           ROUNDNESS     FLATNESS     SPHERICITY'/)
           EN=N
           EN1=EN-1.0
           DO 21 I=1,6
           XMO(I,1)=SUM(I,1)/EN
           XM=XMO(I,1)*XMO(I,1)
           XMO(I,2)=(SUM(I,2)-EN*XM)/EN1
           XMO(I,3)=SQRT(XMO(I,2))
         OXMO(I,4)=(EN*(SUM(I,3)-3.0*SUM(I,2)*XMO(I,1)+(2.0*EN)*XMO(I,1)*XM)
         1)/(XMO(I,2)*XMO(I,3)*(EN-2.0)*EN1)
  21     OXMO(I,5)=(EN*((EN+1.0)*(SUM(I,4)-4.0*SUM(I,3)*XMO(I,1)
         1+6.0*SUM(I,2)*XM-3.0*EN*XM*XM))-(3.0*XMO(I,2)*XMO(I,2)
         3*EN1*EN1*EN1))/(XMO(I,2)*XMO(I,2)*EN1*(EN-2.0)*(EN-3.0))
           WRITE(6,22)(XMO(I,1),I=1,6)
  22       FORMAT(1HO,4HMEAN,16X,3(4X,F8.3),3(9X,F5.3))
           WRITE(6,23)(XMO(I,2),I=1,6)
  23       FORMAT(1HO,8HVARIANCE,12X,3F12.3,3F14.3)
           WRITE(6,24)(XMO(I,3),I=1,6)
  24       FORMAT(1HO,18HSTANDARD DEVIATION,2X,3F12.3,3F14.3)
           WRITE(6,25)(XMO(I,4),I=1,6)
  25       FORMAT(1HO,17HSTANDARD SKEWNESS,3X,3F12.3,3F14.3)
           WRITE(6,26)(XMO(I,5),I=1,6)
  26       FORMAT(1HO,17HSTANDARD KURTOSIS,3X,3F12.3,3F14.3)
  101      CONTINUE
           STOP
           END
End of file
```

APPENDIX 3

Mac Cammon formula for graphically derived mean grain size.

$$\frac{\phi 5 + \phi 15 + \phi 25 + \phi 35 + \phi 45 + \phi 55 + \phi 65 + \phi 75 + \phi 85 + \phi 95}{10}$$

SAMPLE TR1A.

Graphic Mean = -6.387ϕ = 83.69mm
Moments Mean = -6.362ϕ = 82.25mm
Difference = 0.025ϕ = 1.44mm

SAMPLE T10A

Graphic Mean = -5.516ϕ = 45.76mm
Moments Mean = -5.523ϕ = 45.98mm
Difference = 0.007ϕ = 0.22mm

SAMPLE T20A

Graphic Mean = -5.02ϕ = 32.40mm
Moments Mean = -5.018ϕ = 32.40mm
Difference = 0.002ϕ = 0.05mm

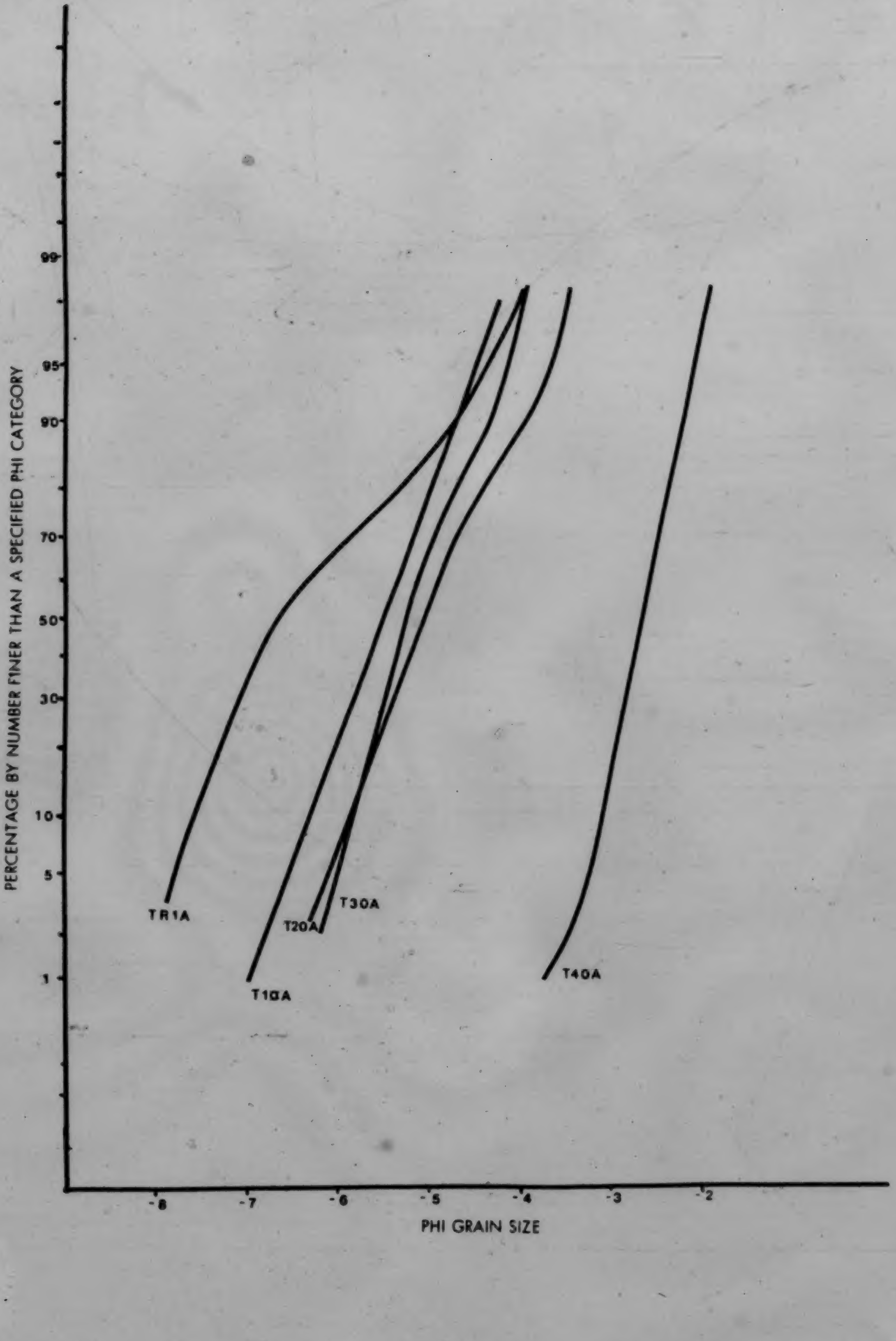
SAMPLE T30A

Graphic Mean = -5.201ϕ = 36.78mm
Moments Mean = -5.254ϕ = 38.16mm
Difference = 0.053ϕ = 1.38mm

SAMPLE T40A

Graphic Mean = -2.694ϕ = 6.47mm
Moments Mean = -2.866ϕ = 7.29mm
Difference = 0.172ϕ = 0.82mm

APPENDIX 3


PERCENTAGE BY NUMBER FINER THAN A SPECIFIED PHI CATEGORY
99
95
90
70
50
30
10
5
1
TR1A
T10A
T20A
T30A
T40A
-8
-7
-6
-5
-4
-3
-2
PHI GRAIN SIZE

APPENDIX 4

Results of Regression of Log. Mean Grain Size on Distance Downstream

Reach	R	R^2	Sig.
Proximal Medial Distal	-0.88912	0.79053	0.00
Inter Fan	-0.89866	0.80759	0.00
Proximal	-0.75196	0.56545	0.00
Medial	-0.71036	0.51892	0.00
Distal	-0.90479	0.81865	0.00
LIMESTONES			
Proximal Medial Distal	-0.89450	0.80174	0.00
Inter Fan	-0.87335	0.76274	0.00
Proximal	-0.76274	0.59001	0.00
Medial	-0.73397	0.53891	0.00
Distal	-0.89890	0.80802	0.00

QUARTZITIC COMPONENT			
Proximal Medial Distal	-0.86783	0.75312	0.00
Inter Fan	-0.86983	0.75661	0.00
Proximal	-0.55442	0.30738	0.006
Medial	-0.62953	0.39630	0.00
Distal	-0.90051	0.81091	0.00
QUARTZITES			
Proximal Medial Distal	-0.63647	0.4051	0.00
Distal	-0.9014	0.8125	0.00

APPENDIX 5

TEST OF PARALLELISM

Large Sample N>30

$$Z = \frac{B_iQ - B_iL}{\sqrt{S^2B_iQ - S^2B_iL}}$$

where:

$S^2B_i = S^2\ Y\ X\ /\ (n - 1)\ S^2X$

$S^2\ Y \cdot X$ = Residual Mean Square Error

S^2X = Sample Variance

B_i = Slope of Regression

Small Sample

$$T = \frac{B_iQ - B_iL}{S_{B_iQ - B_iL}}$$

where:

$S_{B_iQ} - B_iL$ = Estimate of the standard deviation of the estimated difference between slope.

$$S_{B_iQ} - B_iL = S^2_p\ Y\ X\ [\ \frac{1}{(n_Q - 1)\ S^2\ X_Q} + \frac{1}{(n_L - 1)\ S^2\ X_L}\ ]$$

Where

$$S^2_p\ Y \cdot X = \frac{(n_Q - 2)\ S^2\ Y\ X_Q + (n_L - 2)\ S^2\ Y\ X_L}{n_Q + n_L - 4}$$

Quartzitic Component vs Limestones

Proximal, Medial and Distal

Large Sample. N = 88.

$S^2\ B_i\ Q = 0.00286609$

$S^2\ B_i L = 0.0023089$

$B_i Q = 0.0002277$

$B_i L = 0.0002149$

$Z = -0.00017793 < Z_{crit}$

H_0 accepted

Medial

Large Sample. N = 34

$S^2\ B_i\ Q = 0.01893$

$S^2\ B_i\ L = 0.01448$

$B_i Q = 0.000244$

$B_i L = 0.000178$

$Z = -0.000361 < Z_{crit}$

H_0 accepted

Distal

Large Sample. N = 31

$S^2\ B_i\ Q = 0.006527$

$S^2\ B_i\ L = 0.0066095$

$B_i Q = 0.0006348$

$B_i L = 0.0005899$

$Z = -0.00039174 < Z_{crit}$

H_0 accepted

Proximal

Small Sample. N = 24

$S^2_p\ Y\ X = 0.03646$

$S^2\ B_iQ - B_iL = 0.06907$

$T = -0.00045 < T_{crit}$

H_0 accepted.

Interfan

Small Sample. N = 14

$S^2\ Y\ X = 0.02348$

$S^2\ B_iQ - B_iL = 0.04069$

$T = -0.001885 < T_{crit}$

H_0 accepted.

True Quartzites vs Limestones

Proximal, Medial and Distal

Large Sample. NQ = 50, NL = 88

$S^2\ B_i\ Q = 0.00235$

$S^2\ B_iL = 0.0023089$

$B_iQ = 0.000253$

$B_iL = 0.000215$

$Z = -0.000527 < Z_{crit}$

H_0 accepted.

Distal

Large Sample. NQ = 18, NL = 31

$S^2\ B_iQ = 0.011018$

$S^2\ B_iL = 0.0066095$

$B_iQ = 0.006618$

$B_iL = 0.0005899$

$Z = -0.001072 < Z_{crit}$

H_0 accepted.

APPENDIX 6

DIMINUTION AND ABRASION COEFFICIENTS FROM EXPERIMENTS AND FIELD OBSERVATION (IN PART AFTER SHAW AND KELLERHALS; IN PRESS)

Source	Material	km^{-1}	Notes
	ABRASION EXPERIMENTS		
Daubree (in Pettijohn 1957)	granite	0.00036 - 0.0013	abrasion mill
Krumbein, 1941	limestone	0.010	abrasion mill
Wentworth, 1919	limestone	0.0009	abrasion mill
Marshall, 1927	greywacke	0.00014	abrasion mill
Schoklitsch, 1930 (in Graf 1971)	marly limestone	0.00167	abrasion mill
	limestone	0.00100	
	dolomite	0.00083	
	quartz	0.00033	
	gneiss/ granite	0.00050 - 0.00020	
	amphibolite	0.00035 - 0.00020	
Kuenen, 1956	quartzite	0.00006	circular flume cement floor
	quartz	0.00009	
	compact limestone	0.00030	
	compact limestone	0.00040	
	flint	0.0002	circular flume pebbly floor
	quartzite 1	0.0002	various velocities various seds. in suspension
	quartzite 2	0.0003	
	quartz	0.0004	
	siliceous limestone	0.0015	
	limestone	0.0032	
	gneiss	0.0022	
	quartzite 1	0.0003	circular flume pebbly floor
	quartzite 2	0.0005	pebble velocity 113 cm/sec
	quartz	0.00027	
	greywacke	0.0011	
	gneiss	0.0026	
Bradley, 1970	quartz	0.00028	Kuenen-type circular-flume
	fresh granite	0.00031	
	weathered granite	0.0042	

	fresh gneiss	0.00058	
	weathered gneiss	0.0069	
RIVERS			
Heine in Leliavsky, 1966		0.006	River Mur mean particle size
		0.00106	River Mur max particle size
Sternberg (in Leliavsky 1966)		0.004	River Rhine reduction of mean particle weight
		0.007	River Mur
		0.0085	River Iller
Forcheimer (in Graf 1971)		0.0181	River Mur (at Graz Austria)
Schoklistch (in Graf 1971)		0.1054	R. Gail, Austria
		0.0230	River Danube (Austria)
		0.0269	River Traun
		0.937	River Lech
		0.0095	River Seine (Paris-Rouen)
Leopold, Wolman and Miller 1964		0.0327	Rock Creek, Montana, D50
Hack 1957		0.0139	Tye River, Va. D50
Bradley 1970	chert	0.00097	Colorado River Texas
	quartz	0.0015	mean B-axis of coarsest 50 stones
	granite	0.0028	
Nordseth 1973		0.148	River Glomma, Norway (Braided) D50 Gravel only
Shaw and Kellerhals, in press			Total sample D90 central reaches in Alberta Athabasca River
		0.00177	Bow-South-Saskatchewan River
		0.00182	North Saskatchewan River
		0.00300	Red Deer River
		0.00108	Peace River
Kellerhals in Shaw and Kellerhals, in press		0.0398	Columbia River B.C. D90 Stage-discharge relationship confirms aggradation

Alluvial Fans and Ancient Gravel Deposits

Schlee, 1957		0.0542	Upland Gravels Maryland modal Size
Plumley, 1948	metamorphic	0.0417	Rapid Creek, Dakota Terrace Gravels mean Phi
	limestone	0.1116	Bear Butte Creek Terrace gravels mean Phi
Krumbein, 1942		5.840	La Crescenta alluvial fan maximum boulder weight
Krumbein, 1942	granodiorite	0.1226	Arroyo Seco alluvial fan California maximum boulder diameter
Blissenbach, 1954		0.383	Catalina Mt. Arizona. alluvial fan max. particle size
Bluck, 1965	limestone		Ancient Alluvial fan, South Wales max. particle size
		6.6107	upper fan
		2.123	lower fan
Eckis, 1928 (in Allen,1965)		0.5029	Cucamonga, Calif alluvial fans
		0.1284	max. particle size
Yatsu, 1957			Alluvial fans D50
		0.0238	Lower Kinu
		0.0253	Upper Kinu
		0.0416	Lower Watrase
		0.0531	Upper Watrase
		0.0532	Upper Tenryn
		0.0104	Lower Kiso
		0.0348	Upper Kiso
		0.0173	Lower Nagaro
		0.0446	Upper Nagaro
		0.0288	Upper Sho
		0.0715	Upper Abe
		0.0247	Yahagi
		0.11	Upper Makita
		0.024	Hii
Kellerhals (in Shaw and Kellerhals, in press)		0.517	Illecillewaet River, fan. B.C. D90